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# A Technology-aided Multi-modal Training Approach to Assist Abdominal Palpation Training and its Assessment in Medical Education

by

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# Publications

## Papers

- A. Asadipour, K. Debattista, and A. Chalmers, "A game-based training approach to enhance human hand motor learning and control abilities" in Games and Virtual Worlds for Serious Applications (VS-Games), 2015 7th International Conference on. IEEE, 2015, pp. 1–6. ***Invited as one of the best papers to journal of Visual Computer***.

- A. Asadipour, K. Debattista, and A. Chalmers, "The Application of Multimodal Augmented Feedback in Serious Games to Enhance Acquisition of Motor Skills" Extended version of above paper - Submitted to be peer reviewed to a special issue of the Visual Computer.

- A. Asadipour, K. Debattista, V. Patel, and A. Chalmers, "Palpation Training System (PTS): A Technology-aided Multi-modal Training Approach to Assist Abdominal Palpation Training and its Assessment in Medical Education" In preparation to be shortly submitted to the Computer Education.

## Posters

- WMG Doctoral Research and Innovation Conference, Apr 2013, University of Warwick, Coventry

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If you want to achieve success in your life aim high otherwise you will end up accomplishing nothing.

Ahmad Asadipour

# A Technology-aided Multi-modal Training Approach to Assist Abdominal Palpation Training and its Assessment in Medical Education

**Approved by**
**Dissertation Committee:**

# Abstract

Kinaesthetic Learning Activities (KLA) are techniques for enhancing the motor learning process to provide a deep understanding of fundamental skills in particular disciplines. With KLA learning takes place by carrying out a physical activity to transform empirical achievements into representative cognitive understanding.

In disciplines such as medical education, frequent hands-on practice of certain motor skills plays a key role in the development of medical students' competency. Therefore it is essential that clinicians master these core skills early on in their educational journey as well as retain them for the entirety of their career. Transferring knowledge of performing dexterous motor skills, such as clinical examinations, from experts to novices demands a systematic approach to quantify relevant motor variables with the help of medical experts in order to form a reference best practice model for target skills. Additional information (augmented feedback) on certain aspects of movements could be extracted from this model and visualised via multi-modal sensory channels in order to enhance motor performance and learning processes.

This thesis proposes a novel KLA methodology to significantly improve the quality of palpation training in medical students. In particular, it investigates whether it is possible to enhance the existing abdominal palpation skills acquisition process (motor performance and learning) with provision of instructional concurrent and terminal augmented feedback on applied forces by the learner's hand via an autonomous multimodal displays. This is achieved by considering the following: identifying key motor variables with help of medical experts; forming a gold standard model for target skills by collecting pre-defined motor variables with an innovative quantification technique; designing an assessment criteria by analysing the medical experts' data; and systematically evaluating the impact of instructional augmented feedback on medical students' motor performance with two distinct assessment approaches(a machine-based and a human-based).

In addition, an evaluation of performance on a simpler task is carried out using a game-based training method, to compare feedback visualisation techniques, such as concurrent visual and auditory feedback as used in a serious games environment, with abstract visualisation of motor variables.

A detailed between-participants study is presented to evaluate the effect of concurrent augmented feedback on participants' skills acquisition in the motor learning process. Significant improvement on medical students' motor performance was observed when augmented feedback on applied forces were visually presented ($H(2) = 6.033$, $p < .05$). Moreover, a positive correlation was reported between computer-generated scores and human-generated scores, $r = .62$, $p$ (one-tailed) $< .05$. This indicates the potential of the computer-based assessment technique to assist the current assessment process in medical education. The same results were also achieved in a blind-folded (no-feedback) transfer test to evaluate performance and short-term retention of skills in the game-based training approach. The accuracy in the exerted target force for participants in the game-playing group, who were trained using the game approach ($Mdn = 0.86$), differed significantly from the participants in control group, who trained using the abstract visualisation of the exerted force value ($Mdn = 1.56$), $U = 61$, $z = -2.137$, $p < .05$, $r = -0.36$. Finally, the usability of both motor learning approaches were surveyed via feedback questionnaires and positive responses were achieved from users.

The research presented shows that concurrent augmented feedback significantly improves the participants' motor control abilities. Furthermore, advanced visualisation techniques such as multi-modal displays increases the participants' motivation to engage in learning and to retain motor skills.

# Chapter 1

# Introduction

## 1.1 Research Motivation

Human hands are widely used as an exploratory and manipulative tool every day in our early years to obtain sensory information (eg. shape, size, texture, roughness) and to interact with the surrounding environment. Mastering dexterous use of our hands in some motor tasks requires years of training. It is a fact that more hands-on practice is essential in particular disciplines such as medical education to master core skills (eg. clinical palpation) and to retain them throughout a career. However, this process is still unknown to the researchers in this domain due to lack of comprehensive ergonomic studies on hands-on interactions to identify and capture the related metrics.

The highly articulated structure of the human hands provides a vast range of movements. Thus, it is very hard to generalise a captured model of movements of the hand for a particular targeted skills. Moreover, various sensory receptors and their higher concentrations under the hands' tissue adds to the difficulty of studying accurately hands-on interactions. In medical education, physical examination(s) plays a key role in diagnosing diseases from their signs/symptoms in the early stages of the patient care process. Almost all of the preliminary physical examinations involve the use of clinicians' hands and sense of touch to assist in diagnosing various conditions. Therefore it is essential that clinicians master these core skills early on in their medical education (Patel and Morrissey, 2011; Dinsmore et al., 1997) as well as retain them for the entirety of their medical career. Hence medical education programmes focusses on how best to transfer these core skills from the experts to the novices, as well as the assessment process to ensure that a proficient level of core skills has been attained.

The motivation of this thesis is to gain a deep understanding and from this model the dexterous use of hands in specific physical interactions with active involvement of domain experts (eg. medical tutors). The goal is that training with such a derived model may help enhance the conventional motor training processes of others and allow them to be subsequently assessed via an innovative multimodal training system. This is validated by a detailed study to assess the impact of our novel training approach on trainees' motor performance and learning.

## 1.2 Research Problem and its Significance

The majority of the conventional training programmes that teach clinical palpation skills are provided via theory (eg. textbooks), followed by demonstrations prior to practice sessions amongst peer groups. A major challenge is teaching how to detect a wide variety of conditions; however, the peer groups generally are a poor sample of the general population and do not offer a variety of the conditions needed to be studied (eg. enlarged liver) which entails their first experience of such conditions may very well be as when dealing with real patients. Moreover, other challenges such as ethical issues (eg. undressing in front of peers, private conditions which are uncovered by examination of peers, etc.) may affect the training process (Duvivier et al., 2012). Hence, medical students are encouraged to practice palpation skills on alternatives such as fellow students from other courses, family members, mannequins, or cadavers to develop an experience of the correct somatic sensations before performing these skills on a real patient. Without enough proficiency clinical examination may lead to patient's discomfort (eg. prostate cancer palpation) or worse an incorrect or missing diagnosis.

Another challenge is resource allocation based on, for example tutor availability in comparison to the intake of medical students per academic year in England (The Health and Education National Strategic Exchange (HENSE), 2015). In formal training sessions medical students are usually divided into smaller groups supervised by a tutor but this is infrequent. Moreover, in self-study training time (eg. at home) lack of supervision may lead to deviation from correct techniques.

Despite many advances in training approaches, the current gold standard still lacks the provision of the experience that the expert is undergoing when a condition has been detected by the medical students (Coles et al., 2011). Currently this is conveyed via the expert describing verbally the experience of touch and the students attempting to interpret the verbal information to it. Other best practice approaches include the use of physical models such as using a silicone breast modelled with a tumour. This also has other psychological barriers (e.g. it may be difficult for a trainee to relate an artificial body part to a real human being) as the rest of the human body is not there. Although the observer can see the superficial performance of students and try to link their description of the palpation experience with the assumed condition during formal assessments (eg. OSCE), they still need to ensure to what extent the student understood the skills.

One more important factor in training is the regularity of palpation skills training. In research led by Duvivier et al. (2012), students state the importance of frequent rehearsal outside of dedicated training sessions. It has been reported that students devote approximately 14% of their study time to hands-on practice when during self-study out of training sessions (Mavis, 2000). Hence, it is essential to introduce innovative multimodal training approaches to increase the frequency of performing palpation skills as well as providing proficient supervision to minimise the chance of errors during such sessions.

## 1.3 Research Aims and Objectives

The aim of this research is to form a best practice model for palpation examination skills with help of the medical experts and to investigate the potential of an innovative multimodal training technique based on this model on medical students' motor performance. This will serve as a means of providing an enhanced palpation experience for detecting various conditions, as well as an improved method of assessment. This research will focus on various abdominal palpation tasks via a haptic-enabled tutoring interface with multimodal feedback on hands-on interactions for training purposes. The following objectives were planned in this research to achieve the research aim:

- Understanding the importance of clinical examinations and the existing challenges.
- Identifying hands-on interaction metrics and quantifying them with a novel measurement technique.
- Analysing the captured data with the help of medical experts to form a best practice model for target palpation examinations and to create an assessment criteria.
- Investigating current state-of-the-art on human hand ergonomics to select/design a customisable measurement interface.
- Develop a proof of concept multimodal training and assessment approach.
- Evaluating usability of the proposed innovative training approach through a pilot study with medical students.

## 1.4 Contributions

This work proposed a proof of concept for the use of multimodal augmented feedback in training motor skills, particularly to enhance conventional processes in learning and assessing clinical palpation examination. These research contributions are outlined as follows:

- Identification of palpation metrics,
- Elicitation of study requirements with help of medical experts,
- Invention of a novel measurement technique to quantify hands-on interaction,
- Creation of the best practice model for target palpation examination tasks,
- Identification of assessment criteria for target palpation tasks with guidance from medical experts,
- Evaluation of different multimodal visualisation strategies in learning motor skills.

## 1.5 Thesis Outline

A brief overview on the rest of thesis chapters are presented as follows:

- Chapter 2 presents an extensive literature review on aspects of human learning particularly in motor skills, the impact of additional multimodal feedback on the motor performance, and the existing unimodal and multimodal training strategies and their visualisation techniques.

- Chapter 3 provides a more focused review on the related studies in human ergonomics, design suggestions, identification of hands-on interaction metrics, and the application of multimodal training methods in medical education.

- Chapter 4 covers the widely used ergonomic and user-centered design methods with the capability to actively involve actual users in design and evaluation processes. User and task specific requirements are elucidated to enhance the reliability and robustness of the research methodology.

- Chapter 5 proposes a cost-efficient and robust measurement technique comprised of a capturing approach to acquire the human hands metrics during interaction with the environment and an approach to assess motor skills compared to a best practice model.

- Chapter 6 highlight the steps that are taken in the identification of user requirements, development of the assessment criteria from captured data, and the development of a gold standard (ground truth) model for abdominal palpation examination.

- Chapter 7 presents a systematic usability evaluation of the proposed training model to highlight any potential improvements on medical students' abdominal palpation examination performance.

- Chapter 8 investigates the application of a haptic-enabled serious game training on user engagements and their improvements in learning motor skills as compared to computer simulations.

- Chapter 9 concludes the thesis outlining contributions, limitations and future work.

Also, figure 1.1 presents an overall picture of the research methodology which is described in chapter 4.

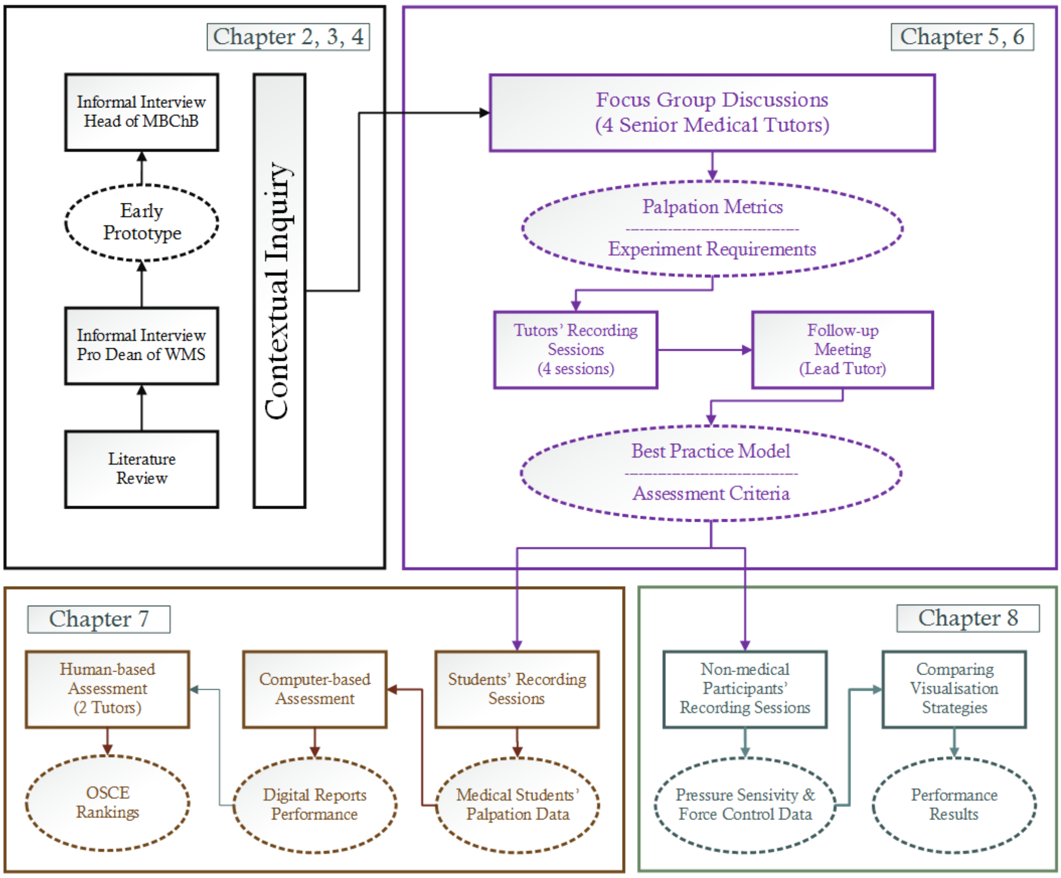



Figure 1.1: Research Methodology - procedures are presented by solid rectangles and predicted outcomes are illustrated by dashed ellipses

# Chapter 2

# Background

This chapter covers general aspects of human learning with particular focus on the motor learning. Different types of control strategies were presented with a brief review on role of sensory-motor feedback in the human information processing system. Finally, various unimodal and multimodal presentation strategies were discussed to highlight their advantages and disadvantages as well as their efficiency on motor performance and learning acquisition processes.

## 2.1 Introduction to Human Learning

This section presents a widely used psychological model of the human cognitive process of learning to highlight knowledge acquisition levels and different methods to deliver it.

### 2.1.1 The Cognitive Process of Learning

The first step to enhance educational procedures is to study the human cognitive process in depth. Therefore, it is mandatory to identify which cognitive processes are involved in knowledge acquisition, and its retention, by use of a standard model. In a collaborative project led by Bloom and Krathwohl (1984) with educational psychologists, a taxonomy of educational objectives in the cognitive domain was proposed in 1956. Cognitive process was broken down into six categories from simple to complex; *Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation.* This framework became widely known and translated in different languages as a common standard to classify and test curriculum objectives.

Forty five years later the framework has been revised to add a new dimension by cutting ***Knowledge*** across subject matter lines as a new dimension. As a result, a two dimensional taxonomy table was proposed to demonstrate which cognitive activities are involved in various types of knowledge acquisition steps (*Factual, Conceptual, Procedural, and Metacognitive*). The original cognitive terminologies were also simplified and renamed in new revision *Remember, Understand, Execute, Analyse, Evaluate and Create.* Among six categories the middle four are mentioned as the most important cognitive activities in the human learning process (Krathwohl, 2002). Figure 2.1 shows a combined version of the original Bloom's taxonomy and its revision.

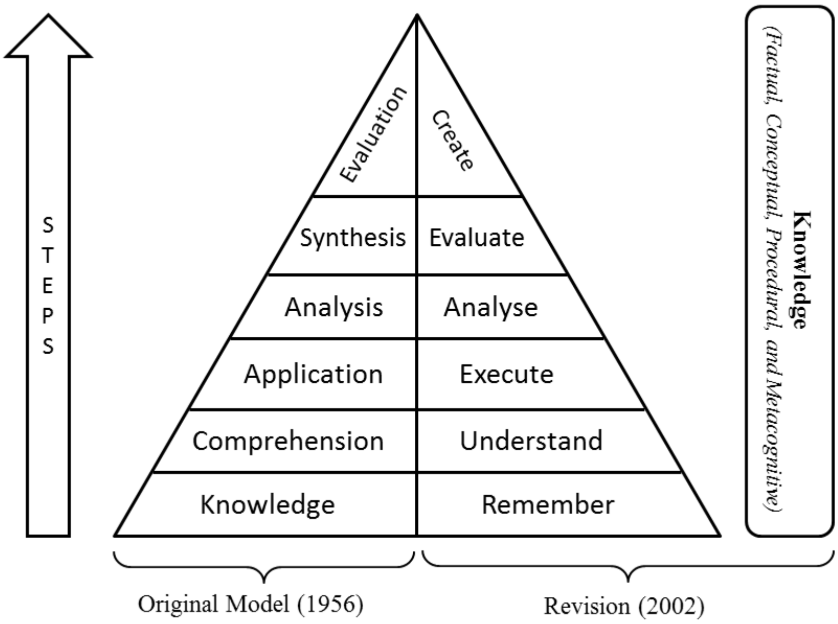



Figure 2.1: Taxonomy of Educational Objectives

### 2.1.2 Classification of Learning Styles

The continuous alterations in higher education development patterns led researchers to continuously modify and evaluate the teaching-learning model. Moreover, recent growth in innovative learning resources (e.g. online learning resources) emphasises the vitality of these studies. According to the (Collier, 1985) teaching methods are divided into five categories:

- Didactic instruction in the form of lectures
- Discussion techniques
- Practical work in the field/laboratory/studio
- Provision for the students' private study
- Assessment of students' progress

Depending on the educational objectives, learning could be achieved by either one or more combinations of the above methods. For instance lecturing is the most effective way to deliver theoretical subjects (e.g. maths, statistics, physics) but additional methods are demanded when knowledge is a product of physical activities (e.g. necessary steps to build a chair as a carpenter). Henceforth, two of the most common methods of learning are presented to debrief the reader about existing learning styles.

#### 2.1.2.1 Conventional Learning Activities

*Lecturing* is widely used and commonly critiqued as the most efficient learning method (Hartley and Cameron, 1967). Since it has an essential function in university teaching (Committee et al., 1964), transitioning to other learning methods is very challenging for curriculum designers. Naturally, lectures are not expected to deliver comprehensive knowledge of a presented topic, but they are acting as a starting point for further self-learning. Moreover, since this is a teacher-oriented approach, which means that the students performance in obtaining the target knowledge vary by the style of lecturer and his competency in delivering materials.

The most commonly used perceptual sensations to acquire information in this method are vision and audition (eg. lectures, seminars). Hence, difficulties may occur in traditional lecturing particularly when learning is derived from physical interactions with the environment (such as learning motor skills). Therefore, the necessity of enhancing conventional methods with some new adjustments becomes apparent, the resolution devised by researchers for this is discussed in the next section. Moreover, rapid growth in the use of technology-aided learning methods (e.g. computer simulations and game-based trainings) in current studies brings a need to revise conventional learning styles.

#### 2.1.2.2 Kinaesthetic Learning Activities (KLA)

KLA is an innovative technique to enhance the learning process for a deep understanding of fundamentals in particular disciplines. With KLA, learning takes place by carrying out a physical activity to transform empirical achievements into representative cognitive understanding. In particular disciplines, such as medical education, more hands-on practices are compulsory to master the core skills (e.g. clinical palpation) and to retain them in their lifelong career. There are representative examples of employing this technique in a variety of learning environments which will be discussed in the next section. This research intends to study KLA activities in current medical education and to investigate the efficiency of KLA with provision of additional multimodal feedback in order to enhance motor performance and learning abilities in medical students.

## 2.2 Introduction to Human Motor Learning

As noted earlier in the previous section when educational objective targets the capability to perform skilled works, learning will be directly achieved by experiment or practice via a series of motor actions which is known as *Motor Learning*. Once a person learns some activity by physical practice, it is not going to be forgotten shortly (eg. driving a car or riding a bicycle). Hence, motor skills are retained relatively permanent soon after mastering them via frequent rehearsal. An analogy is given by Schmidt and Lee (2005) to simile the non reversible nature of the obtained motor behaviours to the difference between an egg and a boiled egg. In addition, direct observation of the learning process is reported as nearly impossible (based on the authors' current knowledge) and it should be inferred to the changes in learner's behaviour (Schmidt and Lee, 2005).

### 2.2.1 Classifications of Motor Skills

The initial step in research on motor behaviour and control is to classify motor movements and tasks for better understanding of terms and to consider their dependency on the kinds of performances that take place. Thus, two classifications are proposed for motor skills: classification by particular movements; classification by perceptual attributes (Schmidt and Lee, 2005).

Three types of movements are presented in the former classification as *Discrete, Serial, and Continuous.* Discrete movements are the motor actions that a user can recognise from their initiation and termination point such as car gear shifting. Serial movements are described as a series of individual movements that are tied together to form an action like playing a guitar. Finally, continuous movements in which the start and end point of the actions are not recognisable such as swimming (Schmidt and Lee, 2005).

The second type of classification is based on predictability of the environmental changes on subject's planning for motor movements. Motor skills are represented by a continuum that ranges from unpredictable to predictable environments. *Close Skills* in which the environment is fairly stable allows the subject to plan for movements in advance (e.g. Bowling). *Open Skills* in which the precise plan for movement is influenced by last minute changes in the environment may differ from the generally predicted plan (e.g. driving in a busy road). Farrell (1975) proposed the necessity of rapid adaptation to the environmental changes in open skills whereas more stable performances in close skills based on subject's observations.

### 2.2.2 The Information Processing Theory

An information-processing model of the human functioning is proposed based on a computer metaphor to breakdown the human motor-control process into separate stages: input; processing; and output (Schmidt and Lee, 2005). This model became very popular in recent cognitive-psychological studies in which researchers are interested to unravel the link between perceived information (stimulus) via the sensory system and the generated motor action (response) by focusing on the processing stage of this model. Figure 2.2 shows this box model and which is designed based on the stimulus-response (s-r) tradition.

Apparently this is an abstract way to study human motor behaviour since internal information processing is not directly observable. Thus, it is essential to

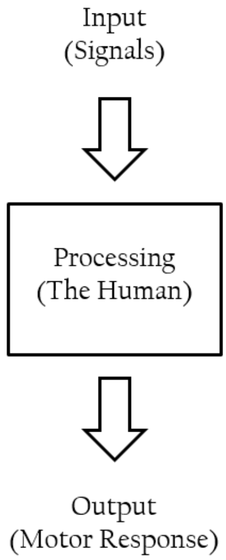



Figure 2.2: Information processing model of functioning

form knowledge of human motor behaviour by monitoring behavioural changes under different experimental conditions. Depending on the target of the research study some approaches are focused on the information flow in different stages whereas others are studying temporal aspects of human information processing such as reaction time.

### 2.2.3 The Sensory-Motor Control Theory

The human sensory-motor process is also described by the interdisciplinary concept of *Control Theory*. Two control strategies are introduced in this theory for a system: an open-loop strategy in which the system is designed for simple processes without self-correction capabilities; and a closed-loop strategy in which the system outputs are continuously measured and reported via a feedback loop to adjust the system inputs in order to achieve the desired goal. The latter category of control systems are learning from the impact of their output on the environment.

The human sensory-motor control system is referred to as a closed-loop control system (Schmidt and Lee, 2005) in which the impact of motor-movements on the environment are constantly monitored by human sensory inputs (eg. vision, audition, touch) to regulate the next motor actions in order to achieve the desired goal. For instance, in a snooker game the player uses her visual perception in each round of the game to adjust her motor movements to achieve maximum game points. Figure 2.3 shows a multilayer representation of the human sensory-motor control system which is adapted from the original model.

The involvement of both control strategies in the human sensory-motor system decisioning process were also surveyed in the current literature. In a research

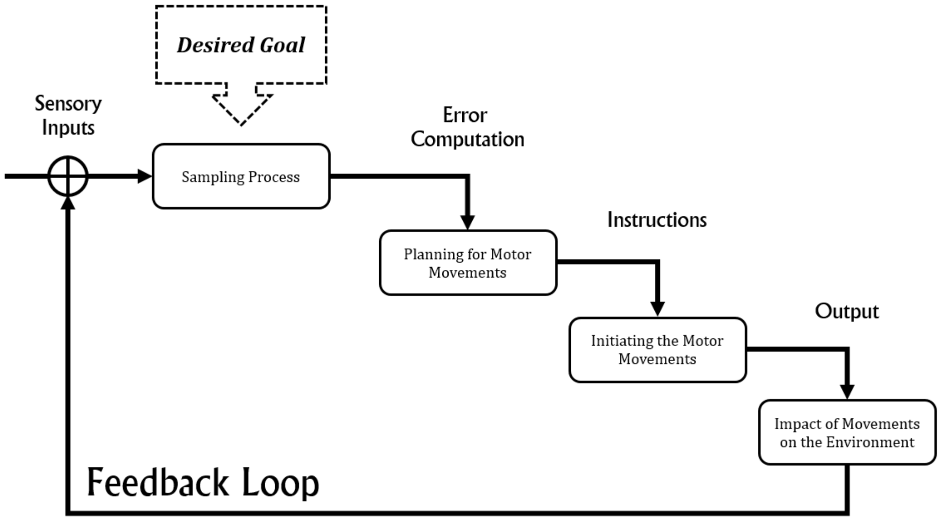



Figure 2.3: The Human Sensory-Motor Control System

led by Collins and De Luca (1993), in order to study postural sway, a quiet standing posture was asked to be adopted of young and healthy subjects. Center-of-Pressure (COP) was defined as measurement variable to represent the whole body dynamics and displacement on a force platform was plotted over time to form a stabilogram-diffusion plot. The study results revealed that the use of two distinct neuromuscular control strategies was needed in maintaining postural balance by participants. Open-loop control strategy was utilised by subjects in short-term intervals with higher stochastic/random activities (loosely regulated) whereas closed-loop strategy was employed in long-term intervals.

### 2.2.4 Classification of Sensory Information

As noted already, the role of sensory inputs in a closed-loop control system is vital to feed the internal information process loop. The system could not be able to plan for the next motor movements towards the desired goal without observing the changes of the previous motor movements on the environment. In physiology, human senses are categorised into three groups based on the source of information: Interoceptors; Exteroceptors; and Proprioceptors (Kammermeier et al., 2001; Schmidt and Lee, 2005; Kozma and Freeman, 2003).

Interceptors are responsible to collect information from the internal organs (via visceral nervous system) that are mostly less important for the information process loop in a sensory-motor system. The second category comprises of the classical five senses of the human (vision, audition, touch, smell, and taste) which are responsible to collect information from external sources (the environment) during physical interactions. Finally, proprioception or kinaesthetic sense which refers to one's own sense of body position in the spatial domain and the force motion from receptors in muscles, tendons and joints (via the vestibular nervous system).

The motor related sensory information is also classified into three categories according to their acquisition/presentation time. The first category of the collected sensory information form an preliminary knowledge to predict the outcomes before planning for appropriate motor movements (pre-practice). The second category is concurrent information that is collected during motor actions from changes in the environment caused by movements (within-practice). Finally, the last category of the sensory information is collected at the end of an action to observe the impact of performed motor movements on the environment (post-practice).

### 2.2.5 Classification of Motor Learning Feedback

In general, sensory-motor feedback is classified by research studies (Schmidt and Lee, 2005) into intrinsic to the individual (***Inherent Feedback***) or could be provided as supplementary to one based on his motor behaviours (***Augmented Feedback***).

The former type of feedback is suggested to be a very clear, rich and immediate source of information (due to its intrinsic nature) that helps one in self evaluation of motor movements which is referred to as *Subjective Reinforcement* (Adams, 1971; Welch, 1985). For instance, soon after a free-kick in a football match, the player could predict the potential outcomes and observe the final impact of his motor action. Even if he does not score a goal this information forms a reference model in his recognition to correct the motor movements in future attempts.

The latter is also addressed as additional or alternative feedback which are represented to the individual in order to enhance learning and performance process. Bilodeau (1966) describes augmented feedback as the most important variable in learning motor movements apart from the practice. For instance, when a driver exceeds the speed limit a beeper sound could alert him to slow down and press the accelerator pedal gently (auditory cues). The information could be visualised in the form of numeric scores for complex routines in a gymnastic competition (visual cues). This research is focused on the use of this type of feedback on aspects on motor learning in medical education. Augmented feedback and its applications on motor learning is discussed in depth in section 2.3.

## 2.3 Augmented Feedback and Motor Learning

Augmented Feedback (AF) is defined as the external source of information (such as a trainer or a feedback display) that helps one to understand certain aspects of motor movements and their impact of the environment within the learning process (Sigrist et al., 2013). AF aims to gradually minimise the variability in a closed-loop control system via sensory feedback loop for the newly developed motor skills. Three phases of learning are suggested by Fitts and Posner (1967) in the process of mastering a new motor skill. A learner starts with understanding the motor actions and forming a mental image of that skill in the first phase (*Cognitive Phase*). In the next stage the learner employs feedback in practice to acquire competency (*Associative Phase*). The final stage of the learning process is when a learner is competent enough to perform dexterous skills without the necessity of substantial effort, attention or thought (*Autonomous Phase*). Feedback helps the learner to shape complex motor skills from various components of movements by shortening the gap between actual performance and the desired skill in a self-correcting fashion within frequent rehearsals. Thus, provision of AF is widely accepted as beneficial and effective to enhance motor learning (Schmidt and Lee, 2005; Sigrist et al., 2013).

The efficiency and presentation of AF are two paramount features that needs further investigation in motor learning research studies. Therefore, several attributes are proposed by the existing literature to describe augmented feedback dimensions (Schmidt and Lee, 2005). Table 2.1 shows three classification dimensions of the augmented feedback.

Table 2.1: Augmented Feedback - Dimensions

| **Types** | **Presentation Method** | **Presentation Time** |
|---|---|---|
| Verbal or non-Verbal | Accumulated or Distinctive | Concurrent or Terminal |

Augmented feedback is usually provided by a human expert such as a coach to the learner in form of verbal and physical demonstration of individual movements or by a technical display such as an autonomous computer-aided simulator (Sigrist et al., 2013). Presentation based methodology is also important to be selected based on the nature of the target motor actions. For instance, accumulated feedback could be presented to the learner to give overall score for the whole motor performance or distinctive scores for each individual movement (e.g. gymnastic routines). Finally, time of presentation plays a key role in the skills acquisition process either as a real-time instruction during performance (concurrent) or a final score immediately after the performance or with a temporal delay (terminal).

### 2.3.1 Types of Augmented Feedback

In general, two types of augmented feedback are proposed in motor learning research studies as follows: Knowledge of Results (KR) which is normally presented at the end of motor tasks (Terminal); Knowledge of Performance (KP) which is given to the learner during motor interactions (Concurret) (Schmidt and Lee, 2005; Sigrist et al., 2013). Both KR and KP are verbal (or verbalisable) post-movement feedback with key differences in the target type of information and their presentation time. The former is focused on the impact of motor movements on the environment whereas the latter delivers information about patterns of the movements within a motor action. However, it is very hard to distinguish them in complex motor skills such as gymnastic performance when a particular pattern of movements lead to a specific outcome as the goal of the movements (Schmidt and Lee, 2005). For instance, KP is provided when a football coach instructs a player on how to use his body to create a top spin free kick, whilst a verbal instruction such as ‘you have not made any score at this game’ is a verbal representation of KR.

Prior to describing the use of KR feedback in motor learning processes in depth, it is crucial to clarify the distinction between performance and learning variables. Learning variables are referred to the representation of KR after all temporary manipulation were withdrawn while Performance Variables are mostly focused on the influence of the KR variables while being manipulated during the motor actions (Salmoni et al., 1984).

The typical use of the KR paradigm in experimental research was also studied by Salmoni et al. (1984) with the presence of KR variables in practice followed by a no-KR transfer test to evaluate the subject's learning improvements. The research investigator is responsible to manipulate KR variables normally in a between subjects research design to identify the impact of these variables on subject's motor improvements. At the same time it could be argued that, improvements in performance take place when KR is presented to the learner whereas learning is normally achieved when no-KR trials.

The latter was evaluated as part of a research study on error detection ability by Rubin (1978) to highlight better improvements in learning while KR is not presented. It was also argued that the effect of KR on one's perception could add judgemental noise, hence, signal detection ideas should be incorporated with the original Schmidt' theory (Schmidt, 1975). Although, some arguments were risen that research on KR may not provide sufficient understanding for the human learning process in complex motor skills (since most of the research studies were focused on one-dimensional tasks) (Fowler et al., 1978), it is undeniable that research on KR is still the most widely used method to determine human behaviours in simple motor skills.

In contrast, KP was introduced by Gentile (1972) to describe the effect of augmented feedback on one's movement patterns while performing a motor action to determine improvement in performance. Despite the proven benefits of the use of KR in motor skills acquisition, the advantage of using KR over KP was always questionable for researchers. The infancy in employment of KP in practice was highly influenced by difficulty in quantification of movement patterns. Moreover, it is dramatically hard to keep track on alterations in movement patterns in subsequent tests while the outcomes could easily be charted in KR before next trial. KP is addressed as an efficient method to teach complex motor movement since it attracts an external focus of attention (Shea and Wulf, 1999). Moreover, the guiding nature of concurrent feedback could ease the complexity of learning new skills in the cognitive phase (Huegel and Malley, 2010).

The advent of sophisticated computer-aided and biomechanical technologies in the previous century facilitates the use of KP in recent studies since the majority of the conventional methods of presenting KP (e.g. filming analysis, strip charts) were failed to show a positive effect on motor learning. Herein, some of the common presentation methods for KP feedback are described.

***Video Feedback*** is a traditional method of presenting KP (Schmidt and Lee, 2005). However, the majority of the research studies were failed to demonstrate the positive effect of video feedback on motor performance (Newell, 1981; Rothstein and Arnold, 1976). Also, it was even reported by Ross et al. (1985) to be disruptive in process of forming cognitive understanding of motor movements particularly when it is combined with other sources of information (such as observing a correct model of movements). Moreover, in complex motor skills the learner may lose his/her attention on what is important, when too much information is presented.

Therefore, the use of additional information (attention-focusing and error-correction cues) in conjunction with video feedback were suggested by Kernodle and Carlton (1992) to boost the effectiveness of this type of augmented feedback. In their experiment, subjects were asked to throw a sponge ball with their non dominant arm as far as possible along a straight line with closed eyes at the release time, hence, they were not allowed to observe the ball's trajectory. Subject's were randomly assigned into four groups with provision of different augmented feedback; KR only , KP only , KP with attention cues, and KP with transition. Throwing distance was measured to assess subjects' performance and throwing form were rated by untrained judges. The throwing distance was verbally presented by the experimenter to participants in the KR group after each trial. The second group received video replay of their throwing pattern as KP to monitor their just-completed trial. The third group benefit from cues on where to focus before viewing the just-completed trial. Finally, subjects in the last group have received instructions on how to correct their movements before viewing the video feedback. The authors concluded that the best performances were achieved when video feedback was accompanied by additional information (attention-cues and error-corrections).

***Kinematic Feedback*** is movement-related aspects of one's performance (Center Of Pressure (COP), position of body limbs, and etc.) that describes pure motion (Schmidt and Lee, 2005; Lauber and Keller, 2014). Kinematic feedback ranges from loosely measured information from experts based on their observation (eg. a coach, an instructor, or a tutor) to highly accurate measurements from electronic sensors (Inertial Measurement Unit or IMU sensors). Kinematic feedback usually conveys information of how to correct movements in order to achieve the predefined desired goal of motor movements (eg. hitting a ball with tennis racket). The instructive nature of this form of feedback demands the involvement of experts who can detect ***What Went Wrong*** during learners' motor performance. The potential use of kinematic feedback on performance improvements was researched early on 19th century by Lindahl (1945). Foot-pedal motion patterns were monitored and modelled with help of skilled workers while they were operating an industrial cutting machine to form a best practice model (aka gold standard). This model was used later in his study to facilitate conventional industrial training by providing kinematic feedback to the new employees (apprentices). His study outcomes revealed very promising achievements by new employees while they were able to perform competent motor actions as good as skilled workers after only 10 weeks of training with the new method whereas 9 months training was needed in the conventional training scheme.

As Newell et al. (1990) pointed out, prior familiarity with the desired goal of motor task will affect on the effectiveness of providing additional information (eg. task criterion and augmented feedback). In their study subjects were asked to draw two geometrical shapes: a circle and an unknown novel shape. Participants were assigned into three groups with various combinations of additional information as follows: Error between learner's drawn shape and the desired goal (KR); a digital image of movement pattern to draw a shape (criterion) plus KR; and a digital image of the produced movement patterns by the learner on the criterion template plus KR. Absolute integrated error as measured to assess the motor performance. It was concluded by Newell et al. (1990) that when the criterion is well-known to the learners (a circle) augmented feedback are less likely to be influential in learning and performance processes but significant improvements were reported for the third group which benefits from augmented feedback (KP) when the task goal was unknown to the learner (irregular shape).

***Kinetic Feedback*** is also another form of KP that conveys information about locomotion forces, torques over time (moments) in organisation of motor movements. This type of augmented feedback is widely used to boost one's motor performance. Particularly, various studies were focused on force feedback to evaluate its impact on learning and performance processes (Lauber and Keller, 2014). Howell (1956) proposed a technique to facilitate a runner's sprint start training by comparing the runner's performance (the generated force-time pattern) with the ideal practice with graphical representation of the force-time curves. The runner's applied forces on the surface of the starting block were measured with help of surface mounted force sensors. Significant improvements to generate maximum impulse was reported in his study for the experimental group which benefits from graph analysis. In another study on voluntarily contraction of quadriceps muscles by Peacock et al. (1981) in the presence of force feedback subject's isometric force was measured with a hydraulic dynamometer in a sitting position. Four trials were planned with one of the following configurations: no feedback, visual feedback (value on a dial), auditory feedback ("push harder"), and a combination of both visual and auditory. Within-subject analysis results indicated a greater torque generation in presence of feedback in their study.

***Biofeedback*** is a comparatively newer form of feedback that delivers information about physical responses to motor actions (eg. heart rate, blood pressure, brain activity). This form of KP is mostly focused on biological aspects of the human motor performance and recent progress in development of biomedical sensory quantification tools such as wearable heart rate monitoring wrist bands or sophisticated scanning devices (eg. EEG and fMRI) had a great impact on employment of this feedback in research studies.

### 2.3.2 Frequency of Presentation

Despite the effective role of augmented feedback in acquisition of motor skills too frequent concurrent feedback (KP) were reported to be disruptive in learning process since it may create dependency on feedback. In this condition learner's attention is attracted to the provided feedback instead of the inherent feedback from task intrinsic perceptions (Sigrist et al., 2013). Thus, the use of concurrent feedback (KP) were suggested with provision of multiple delayed terminal feedback (KR) and no-feedback trials (transfer test) to minimise the learner's reliance on extrinsic feedback. Therefore, three methods were suggested by the literature (Sigrist et al.,

2013) as below:

- ***Fading Feedback:*** it is suggested to gradually reduce the use of augmented feedback overtime. However, the optimum reduction rate is usually unknown to the experimenter. Also, the pre-scheduled nature of this method is not tailored to the learner's needs, hence it is advised to present augmented feedback based on the performance improvements within the learning process.

- ***Bandwidth Feedback:*** this method benefits from presentation of augmented feedback in the event of error occurrence or when the learner exceeds a predefined threshold. Bandwidth feedback is reported to be effective since it motivates the learner to repeat good trials. however, it is not trivial to set the error threshold and distinguish error caused by noise to avoid them to hinder the learning.

- ***Self-controlled Feedback:*** users are in full control to request for augmented feedback in this approach. The advantage of this method is more attention to learner's needs rather than bombarding them by information. Since the learner could relate the received augmented feedback to her achieved performance this may promote the self-efficacy ability

Sigrist et al. (2013) suggested that a short delay in presentation of terminal feedback (KR) may provide enough time for self-estimation of performance and detection of errors but previous knowledge on targeted movements is essential to allow self-estimation of errors. Finally, the augmented feedback should provide information about how to correct errors (prescriptive) rather than the occurrence of errors (descriptive).

## 2.4 Augmented Feedback Visualisation Methods

Provision of concurrent (KP) or terminal (KR) augmented feedback demands a systematically designed visualisation strategies to ensure the additional information does not impair the motor learning process. Thus, it is crucial to choose the most efficient visualisation method and its presentation time based on the influential factors such as learner's competency and task complexity (Timmermans et al., 2009) to enhance the impact of augmented feedback in the motor learning process. Various visualisation strategies were systematically reviewed by Sigrist et al. (2013) to address the advantages and disadvantages of unimodal (vision, auditory, and haptic) and multimodal (combined) augmented feedback displays in motor skill acquisition studies. Vision is commonly stated as the most researched modality that dominates other sensory inputs in perception of spatial information. Recent advancements in technical displays have significantly contributed on employment of the new forms of augmented feedback (eg. auditory and haptic) to facilitate motor training. A brief overview on the human most employed modalities in motor learning's cognitive process is given followed by suggestions on design strategies in this section. The term display is referred to any device with the ability to present augmented feedback through sensory channels such as visual displays (eg. monitors), auditory displays (e.g speakers) and haptic displays (eg. force feedback devices).

### 2.4.1 Visual Displays

Vision is cited as the most important modality as a natural and easy way of acquiring spatial information in one's sensory-motor cognitive process (Sigrist et al., 2013). Its vitality is known as a fact since one could consciously switch off the stream of information from this modality by closing his/her eyes and walking for few steps. In general, two types of visualisation strategies were introduced for representation of relevant motor variables: Abstract and Natural.

#### 2.4.1.1 Abstract Visualisation

Abstract visualisation is normally used in motor tasks with small number of variables. The representation of these variables are range from one dimensional visual cues (eg. bars, gauges or curves) on a normal monitor in simple tasks to more sophisticated two dimensional plots for demonstration of changes over time (eg. acceleration plots in running). For instance force-time plots were commonly used in manual therapy in order to demonstrate live deviation from target colour or shaded bands of acceptable force-range (Sigrist et al., 2013). Another important feature to avoid misinterpretation of visual cues is to respect the common metaphors in design stage. For instance, red, amber and green are usually employed to deliver wrong, caution and right message to the human user. Figure 2.4 illustrates the use of progress bars and numerical values in provision of abstract visual feedback on exerted forces by index finger tip. The learner could visually see the deviation from the desired force in Newtons and the applied forces.

As Sigrist et al. (2013) has pointed out it is important to identify key feature of movement (eg. via an ergonomic study) and to limit feedback only to those features since overwhelming the learner by too much information may degrade the efficiency. In a study led by Schmidt and Wulf (1997), continuous concurrent visual feedback was visually provided in a simple lever arm movement task. Participants who have received concurrent visual feedback outperformed those in the no-feedback category.

#### 2.4.1.2 Natural Visualisation

Natural visualisation refers to three dimensional feedback on spatial and temporal aspects of the movement with ability to superposition or side-by-side presentation of learner's and a reference model (eg. ghosting). Abstract visualisation is not efficient when it is mandatory to feedback on too many variables in a motor task and it may lead the learner into a de-motivation mood since it could rapidly become boring (Sigrist et al., 2013). This method benefits from provision of a virtual trainer to impose acquisition of motor skills in a learning by imitation fashion. Hence, learner observes movement patterns (eg. body, limbs or end effectors) in a motor task in a comparative way on a visual display to mimic actions simultaneously. However, less

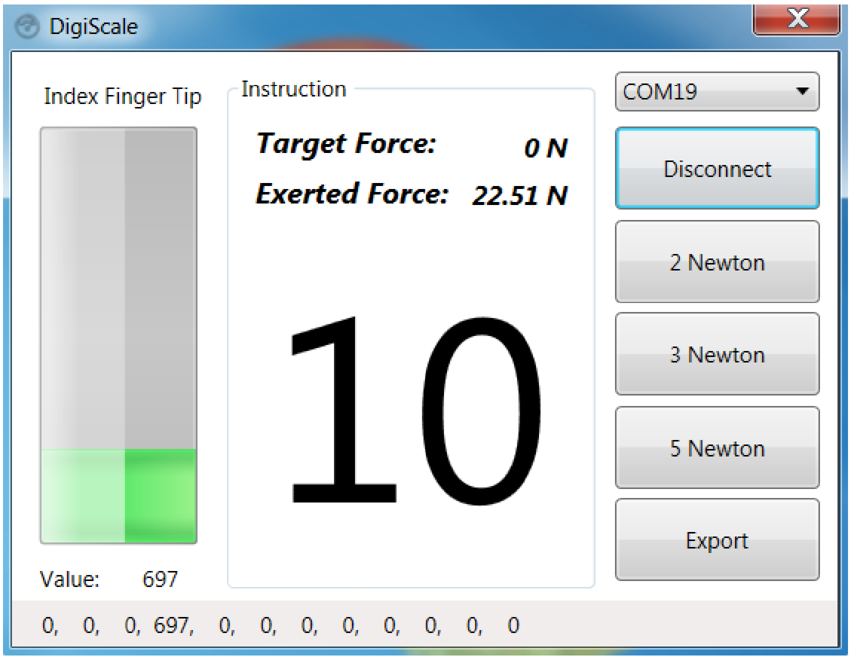



Figure 2.4: DigiScale: an example of abstract visualisation of augmented feedback on applied force by index finger in motor learning

effort has been spent on development and design evaluation of virtual trainers. It is important to avoid superposition of too many parts in design stage since it could overwhelm the learner by delivering too much information (Sigrist et al., 2013). Figure 2.5 shows an example of facilitating motor learning with a side-by-side virtual trainer.

A virtual table tennis simulator has been designed by Todorov et al. (1997) to investigate the impact of natural visualisation of augmented feedback in difficult motor tasks. The systems benefit from fairly realistic animation of complex multijoints movements with a virtual ball and separate paddles for learners and experts. Superposition of learners' racket on experts' pre-recorded performance (virtual trainer) was reported to be effective in learning table tennis shots since the simulator-trained group has outperformed the group with a real coach (Todorov et al., 1997). However, this improvement in performance for simulator-trained group decreased over time in the absence of augmented feedback.

Other features such as position of the virtual trainer and the person's viewing perspective were mentioned to have great contribution on the effective learning of complex motor tasks. It was suggested in a study led by Chua et al. (2003) to place the virtual trainer beside or in front of the learner's avatar when whole-body movements in presented Thai Chi gesture and Posture learning process due to failure in a similar study with superposition of the virtual augmented feedback. Salamin et al. (2010) have shown that first-person perspective may involve other neural processes that may lead to degrade performance in motor learning. Thus, a third-person viewing perspective was suggested in the design stage of natural visualisation.

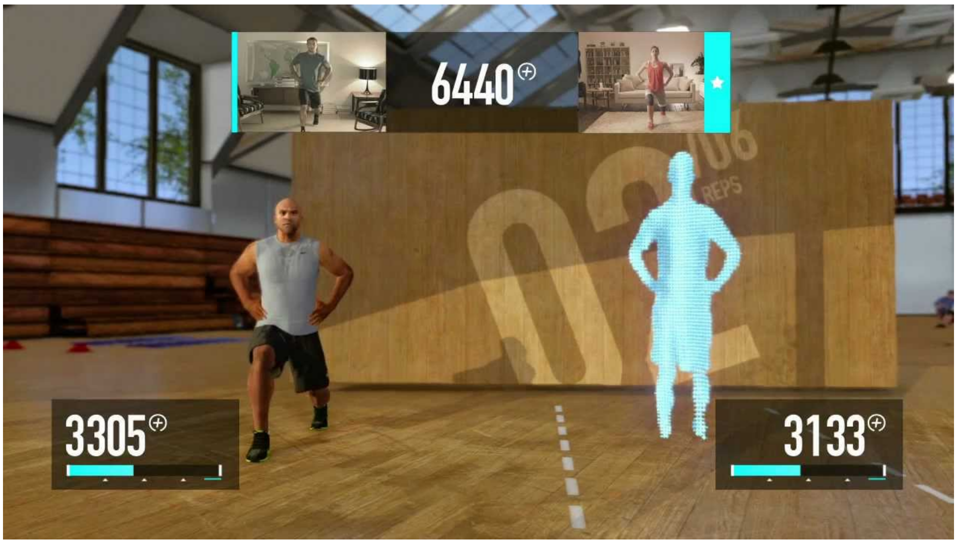



Figure 2.5: An example of natural visualisation of augmented feedback with virtual trainer. Image courtesy of Nike+ Kinect Training Game (Sumo Digital Ltd, 2015)

### 2.4.2 Auditory Displays

Visualisation of augmented feedback via auditory cues are less common yet very effective in the motor learning process (Sigrist et al., 2013). Presentation of sensory information acoustically helps reducing the overload on other modalities during cognitive process of motor skills. Auditory feedback is effective in motor learning when metaphors are carefully chosen to avoid any misinterpretation from learners. Various types of audification strategies were suggested in current literature based on type of information to be delivered. Three type of auditory displays were introduced in a review by Sigrist et al. (2013) as follows: Auditory alarms; sonification of movement variables; sonification of movement errors. The term sonification refers to modulation of sound parameters to represent data values, hence the first type of auditory displays are normally used when no modifications are needed. A brief description of each audification strategy is described in this section.

#### 2.4.2.1 Auditory Alarms (Audification)

Audification of movement variables is usually employed to alert a learner if a predefined threshold is exceeded. In this method values are directly converted to sound parameters in the human perceivable spectrum. The effect of auditory alarms on in gait learning (to regain muscle activity on affected leg) was investigated by Batavia et al. (2001). A twelve and half year old patient with medical history of spina bifida (gap in the backbone around spinal cord) was asked to walk along a mat with embedded pressure sensors to record their walking pattern and a do-it-yourself device comprised of a mini buzzer and a thin pressure-sensitive sensor was placed under her left shoe heel. The buzzer generated an auditory alarm whenever it was triggered by patient's weight. The study has revealed success in shortening the physical therapy duration compare to conventional method.

#### 2.4.2.2 Auditory Feedback on Movement Variables (Sonification)

Another approach in presentation of auditory feedback is sonification of movement variables by mapping their value to sound parameters. This method is particularly beneficial when large amount of variables are captured within a motor task (Sigrist et al., 2013). Sonification of movement variables were reported to be effective on training particularly when performer coordinates the movement dynamically based on a sequential timing pattern. Dragon boat racing is a good example of synchronisation of motor movements (team paddling) with perception of auditory cues which indicate the time pattern by a drummer (see Figure 2.6).


Figure 2.6: Auditory cues that are generated by drummer, guide team paddlers to sync their motor movements

#### 2.4.2.3 Auditory Feedback on Movement Errors (Sonification)

Another type of auditory augmented feedback indicates the deviation from a reference to not only increase the awareness on error occurrence but to deliver information on how to minimise it by modulation of sound parameters (eg. change in pitch). Significant improvement in skill acquisition was reported by Konttinen et al. (2004) when deviation from a shooting target was presented by changes in frequency (higher frequency means smaller deviation from the shooting target). Participants' in the auditory feedback group outperformed the group with terminal presentation of final scores (KR) and controls in a four week training with better retention results in further tests.

### 2.4.3 Haptic Displays

The importance of touch perception is unknown to us since it could not be consciously deactivated like vision and hearing by the human. The vital role of touch in our daily life could be more sensible when Anesthesia (numbness) occurs in healthy individuals. The disrupted stream of information from that body limb (eg. hands) significantly affect the ability to perform simple motor skills such as grasping (Robles-De-La-Torre, 2006).

The term Haptic (Greek Απτω) refers to any form of non-verbal ***Kinaesthetic*** (proprioception) and ***Cutaneous*** (tactile) interaction with the environment involving touch. The human haptic sensation (or touch) is one of the most informative senses that allows one to extract information (exploration) and to physically modify (manipulation) the environment during manual interactions (Alahakone et al., 2009; Srinivasan and Basdogan, 1997; Sigrist et al., 2013). For instance, young infants use their hands as an exploratory tool to discover the world around them (Bertenthal, 1996). However, the effect of haptic augmented feedback on motor learning was less exhaustively researched compared to the visual and auditory (Coles et al., 2011b; Sigrist et al., 2013) feedback due to challenges in development of adequately-realistic haptic displays (eg. unlike touch latency is not acceptable) and common belief on domination of vision and auditory on touch information when they are concurrently delivered to the learner.

Various types of haptic displays were introduced by research studies since 1980 (Mussa-Ivaldi et al., 1985) to deliver augmented feedback in motor learning processes mainly on force and torque due to complexity of tactile sensation. Commercially available off-the-shelf haptic displays were also used by researchers in different applications to evaluate the effect of augmented feedback on touch in motor learning. However, lack of systematic evaluations, limited degree-of-freedom, and cost were always common challenges in this domain. Haptic displays ranges from primitive haptic devices such as wearable gloves to monitor hand positions and force applications to more sophisticated systems like CyberForce Workstations. A more broad review on haptic displays is given in the next chapter.

#### 2.4.3.1 Haptic Guidance Strategies

Depending on the type of haptic interactions, complexity of target motor task, and characteristics of the target population (eg. age, experience) different control strategies were introduced to facilitate motor learning via haptic displays (Sigrist et al., 2013).

***Position-Control-Based*** is the most restricted control strategy in spatial and temporal spaces. The aim of this method is to enforce user movements to follow a predefined best practice model. Thus, less experienced learners (novices) without any previous knowledge on the movement patterns or physically impaired subjects with limited control over their body movements (eg. stroke patients) could benefit from this guidance strategy to form a first representation of target movement early on training complex motor skills. One disadvantages of this method is demotivation caused by tightly restricted movements during the motor learning process.

***Beyond Position-Control:*** loosely constrained to completely unconstrained haptic guidance strategies were also suggested in the current literature in order to motivate learners to actively engage in the motor learning process. Scheidt et al. (2000) have shown that certain amount of freedom in spatio-temporal domains may enhance the motor learning.

### 2.4.4 Multimodal Displays

As noted, unimodal augmented feedback strategies were proven to be effective in the motor learning process (Schmidt and Lee, 2005; Sigrist et al., 2013). However, in real-world practice complex motor movements are planned by the human brain based on concurrent sensory feedback in an information processing loop. Thus, researchers believe that multimodal augmented feedback may minimise the cognitive workload by distribution of information in a control system (Wickens, 2002) but in the same time additional information should not overwhelm the process. For instance vision is efficient in perception of spatial aspects whereas hearing could be used to provide temporal information. Different types of multimodal feedback were suggested in current literature that combines simultaneous perception of two or more modalities during the feedback process which are briefly presented hereafter.

#### 2.4.4.1 Audiovisual

Audiovisual augmented feedback is by far the oldest method of training (eg. videotapes, Sat-Nav) motor skills with several relevant movement variables. This method of augmented feedback was reported to be effective in presentation of counter-movement jumps when visual feedback on movement patters and sonification of applied pressure values on a force plate beneath their feet were presented. Participants' in a multimodal group were reported to have a better estimation of jumping height with higher ability to reproduce the same performance (Effenberg, 2005).

#### 2.4.4.2 Visuohaptic

Visuohaptic displays are not only used to deliver augmented feedback but their ability to allow physical interaction with the environment enhances training realism (Sigrist et al., 2013). Particularly in virtual reality simulations the use of synchronised multimodal feedback lead to a greater level of immersion compared to fidelity of single modal feedback (Srinivasan and Basdogan, 1997). In navigation tasks (eg. driving simulations) which requires a high load of cognitive processes visuohaptic relieves the mental efforts and reduces deviation from the desired goal of movements (error) (Srinivasan and Basdogan, 1997). However, no effect on learning was reported in a shape drawing task with visuohaptic guidance despite the achieved improvement in motor performance (movement fluidity). In another study visuohaptic approaches were preferred by participants compared to the unimodal training methods in a ball bouncing game but no improvement on performance was achieved by additional haptic information.

An innovative visuohaptic training technique were proposed by Coles et al. (2011a) to enhance femoral palpation and needle insertion task in medical education. Real practitioner's hands were captured by a fixed camera and placed into virtual reality world to allow realistic interactions with virtual patient's body in an augmented reality approach. Tactile and force feedback were also provided by custom designed end-effectors on commercial haptic interfaces. Objective feedback were collected from seven medical experts with more than five years experience in Interventional Radiology (IR) to evaluate the usability and content validity of this training approach. More questions on non-implemented features were also provided to avoid any bias in results. Positive responses were received from medical experts on the simulation realism and its accuracy but limitations in freedom of movement were declared as weakness. Other examples of this visualisation strategy are presented in section 3.3.

#### 2.4.4.3 Audiohaptic

As pointed out in a study by Lederman et al. (2003), touch-based auditory cues could assist haptic sensation in texture discrimination (eg. perception of roughness). Three exploration modality conditions (audition, haptic, and audiohaptic) were provided to participants in a mixed between-within-subjects experiment to evaluate the effect of each feedback method on correct detection of roughness properties by a rigid probe. Seven stimulus plates were presented which were named in a texture-neutral fashion (eg. Ken, Bob, tom and etc.) to avoid any confusions. Introductory sessions were followed by experimental blocks in which participants were asked to provide corresponding name for the stimulus plates. Faster learning rates were achieved when audiohaptic (bimodal) feedback was presented to the participants (Lederman et al., 2003).

## 2.5 Summary

This chapter presented a review on aspects of the human sensory-motor learning and its control mechanisms. This review provides initial understanding about the information processing in stimulus-response (S-R) activities. The use of computer-aided learning techniques were discussed in motor learning to highlight the impact of augmented feedback on learning and performance. Haptics technologies were also surveyed in different studies to explore the effectiveness of providing additional sensory information to enhance motor learning and its performance.

# Chapter 3

# Ergonomic Studies

Current literature has been reviewed to plan for a novel ergonomic method for studying hands-on interactions in clinical palpations. This is achieved by considering the following: studying the physiological and anatomical aspects of the human hand; defining the clinical palpation metrics that are necessary to be measured during the examinations; and identifying state-of-the-art quantification methods that are suitable to measure these metrics during hands-on interactions. However, majority of the leading techniques were not commercially available to be evaluated or not flexible in design to meet user requirements in this study. Other disadvantages such as bulkiness that may lead to human fatigue, complex calibration procedures, limitation in movement freedom, and extreme costs were also stated in ergonomic studies. This chapter presents a systematic review on the current literature in human ergonomic studies to answer the following questions: ***What should be measured?*** (palpation metrics); and ***How to measure them?*** (measurement technique).

## 3.1 The Human Hands

The human hands are always credited for their effective role on the evolution of the human species and the development of skills (Taylor and Schwarz, 1995). With more than twenty seven degrees-of-freedom (DoF) in movements (Lin et al., 2000), the human hands are considered to be the most articulated structure in one's body. Moreover, their ability to deliver high bandwidth of information through a complex network of underlying sensory organs and the size of reserved processing space in the cerebral cortex (almost equal to the total space reserved for arm, body, and legs) highlight their importance in our every day life (Taylor and Schwarz, 1995). Thus, it is essential to study their physiological and biological aspects in order to unravel the knowledge behind utilising them in complex motor skills. This section presents some mechanical and sensory aspects of the human hands that is used as a guideline in this research to plan for the best ergonomic approach to quantify its metrics during hands-on interactions.

### 3.1.1 Mechanical Aspects

Despite its articulated structure, the human hands are highly constrained in range of movements. Angular displacement around wrist joints were presented by Bunnell (1964) with total range of 122 ° for pitch (78 ° dorsal felexion and 44 ° degrees volar flexion) and 45 ° degrees for yaw movements (17 ° radial flexion and 28 ° degrees ulnar flexion). The rotational mobility in roll action (pronation/supernation movements) were also stated to be 180 ° (when elbow is flexed) to approximately 360 ° (with help of shoulder when arme is fully extended) (Taylor and Schwarz, 1995). Figure 3.1 represents the angular movement constraints of the human hands.

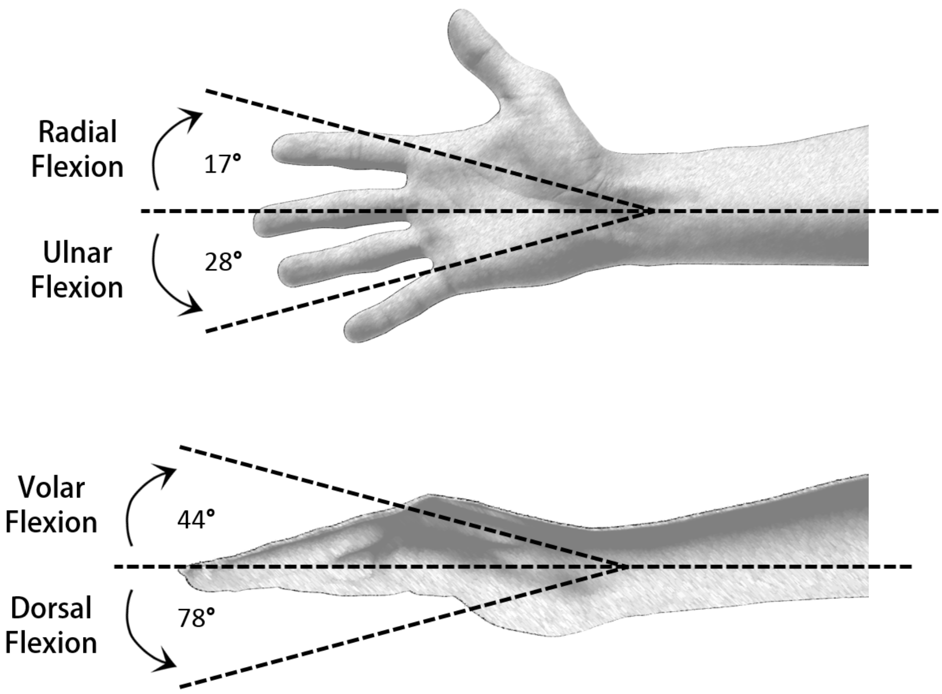



Figure 3.1: The Human Hands' Range of Movements

### 3.1.2 Biological Aspects

Tactile sensations such as vibration, touch and pressure are perceivable by the underlying network of sensory receptors called mechanoreceptors. Four major types of mechanoreceptors (nerve endings) with different adaptation rates and positions from the skin surface are involved in the human touch perception through hands-on interaction. Figure 3.2 indicates the mechanoceptors locations in different layers of the human hands' tissue.

Meissner and Pacinian corpuscles are rapidly adapting mechanoreceptors with ability to detect light touch (eg. stroaking) and vibration whereas Ruffini

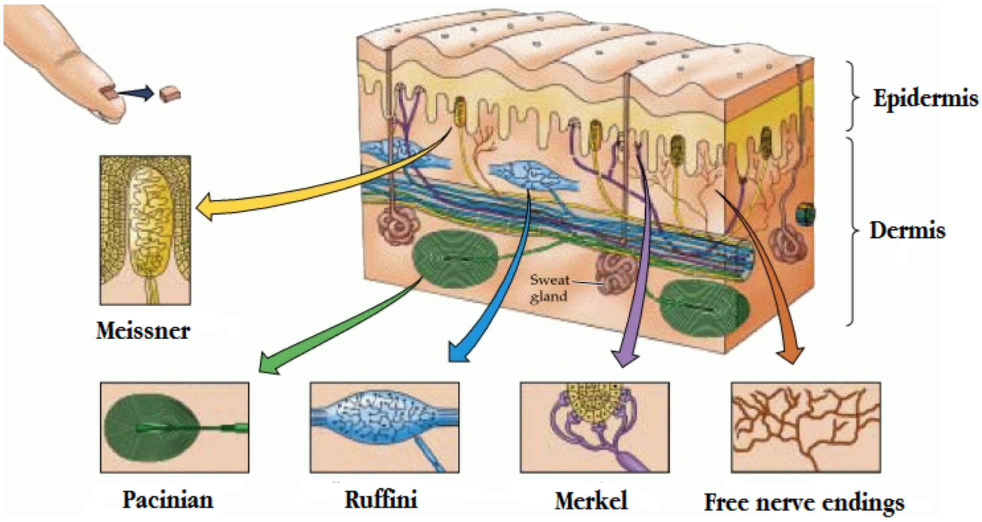



Figure 3.2: Mechanoreceptors locations in superficial and deep layers of the hands' tissue. Image courtesy of (Purves et al., 2001)

and Merkel corpuscles are slowly adapting receptors with sensitivity to pressure (mechanical loads with longer contact durations), texture, and skin stretch (Gardner et al., 2000). Figure 3.3 shows the distribution of the mechanoreceptors on the hand palmar surface.

Fingertips have the highest discriminative capacity with two-point threshold (minimum required distance to discriminate two stimuli) of 2 $mm$ that increases to 10 $mm$ on the palm (Gardner et al., 2000) with higher sensitivity threshold of 2 $gm/mm^2$ as compared to forearm 33 $gm/mm^2$ (Taylor and Schwarz, 1995). Characteristics of other types of tactile receptors such as *Thermoreceptors* (temperature) and *Nociceptors* (pain) have not been reviewed in this research.

## 3.2 Palpation Metrics and Quantification Techniques

In order to study abdominal palpation examinations it is crucial to first identify which key parameters are important to be measured. Since the global location of the patient's abdomen remains stationary during performing examination, it is only necessary to identify metrics that are related to the human hands. Therefore, three important parameters are proposed by both medical and non-medical researchers (Bendtsen et al., 1995; Williams et al., 2012a; Prisacariu and Reid, 2011; Wang and Popović, 2009a; Oikonomidis et al., 2012) as outlined below:

1. ***Position:*** palpating hand's position on the patient's abdomen
2. ***Orientation:*** rotational displacements of the palpating hand
3. ***Pressure:*** magnitude of the exerted forces by different regions of the palpating hand on patient's abdominal surface.

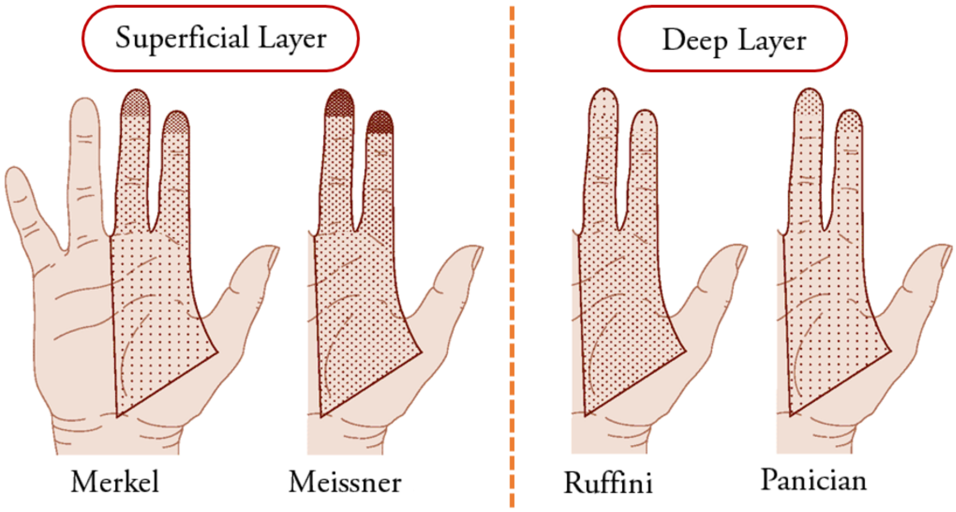



Figure 3.3: Mechanoreceptors distribution on the palmar surface of the human hand. Image courtesy of (Gardner et al., 2000)

The first two parameters are usually referred to as *hand tracking metrics*. The latter was explored by ergonomic studies on the human haptic system to unravel the wisdom of dexterous application of force within physical interactions. Figure 3.4 shows the abdominal palpation metrics and the palpating hand posture during an examination routine.

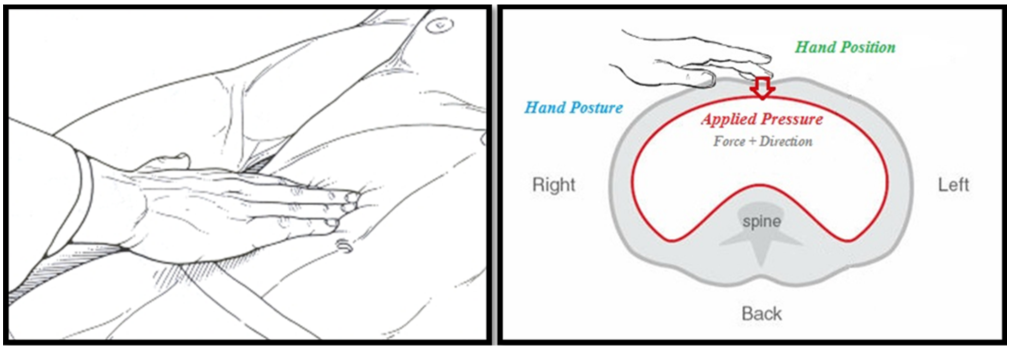



Figure 3.4: Palpation hand posture in an examination routine (left) and the abdominal palpation examination metrics (right)

### 3.2.1 Hand Tracking

Tracking the human hand is a challenge due to its highly articulated structure (Taylor and Schwarz, 1995; Oikonomidis et al., 2012). The measurement process in hand tracking is comprised of global tracking which indicates the position of the whole hand as a structure, and posture tracking which indicates the formation of hand kinematics (bones and joints) in 3D space. In general, two types of tracking methods are introduced; vision-based and wearable-based (Lin et al., 2000). The former is mostly covered by visual motion tracking techniques such as camera-based tracking solutions (eg. Microsoft Kinect, Leap Motion, Sony EyeToy, and etc.) in a marker-based (using a set of sensors or markers) or marker-less fashion with help of image processing algorithms (Frati and Prattichizzo, 2011; Tang, 2011; Prisacariu and Reid, 2011). The latter employs a set of sensors (gyroscope, accelerometer, flex, magnetic and etc.) which are attached to either a glove or fixed by using straps in order to estimate the hand positions/orientations in 3D space without need of any visual based tracking (Dipietro et al., 2008).

Vision-based tracking techniques are either appearance-based or model-based. In the appearance-based approach hand shapes are tracked by analysis of images captured from a camera. Estimation of local motions such as finger movements are challenging in this approach. Another method is to define a model (gradient-based, surface-model, decomposition model) to minimise computational cost of searching in a high dimensional space (Lin et al., 2000). A decomposition model is suggested by Lin et al. (2000) to breakdown the complex hand motions into global motions (the whole hand) and local motions (finger movements) with a constrained structural model to compensate the computational intensive process of tracking. Another method was proposed by Wang and Popović (2009b), uses an ordinary cloth glove with custom pattern of colours to simplify phase estimation with nearest neighbour approach. Their method uses a data-driven technique, a single camera, and inverse kinematic model to recognise hand's gestures and to resolve depth ambiguity instead of traditional marker-based methods such retro-reflective markers or array of overlapping cameras.

Systematic reviews on the glove-based (wearable) tracking techniques were presented in the existing literature (Dipietro et al., 2008; Sturman and Zeltzer, 1994) to highlight strengths and weaknesses of each method and their potential applications. In their review study Glove-based tracking methods were addressed as the most popular tracking techniques as compared to the vision-based approaches since they could minimise challenges such as huge calibration efforts, occlusion of markers, and sensitivity to reflected lights (Dipietro et al., 2008). A glove-based tracker is defined as a typical cloth glove with an array of sensors and electronics mounted to acquire/process the human hand's configurations and motion pattern. Within years the bulkiness of the glove-based trackers were reduced whereas the accuracy of collected data were increased by advancements in electronics and sensory technologies. Thus, more attentions from disciplines such as healthcare were attracted to employ glove-based hand trackers in research studies that involve human motor interactions (eg. rehabilitation, performance analysis, ergonomics and medical education) (Dipietro et al., 2008).

Technical guidelines from hand tracking literature (both vision-based and glove-based tracking) were used in this research to enhance the robustness and reliability of the measurement technique that is proposed in chapter 5.

### 3.2.2 Pressure Mapping

Various types of force sensors/gauges (mechanical, resistive-based, capacitive-based, magnetic-based and etc.) were used in different studies on the human ergonomics to measure the variations in applied forces in physical interactions (Bendtsen et al., 1995; Futarmal et al., 2011; Spyridonis and Ghinea, 2010; Van Den Heever et al., 2009). In a study led by Bendtsen et al. (1995), Pressure-Controlled Palpation (PCP) technique was introduced to monitor the applied pressures by participant's right index fingertip. Variations in applied pressures by different individuals in absence of a standardised model was suggested as a serious problem in learning muscle palpation examinations. Thus, a novel quantification tool (***Palpometer***) was developed and proposed to study these variations. Fourteen physicians were invited to take part in their study in which seven were experienced. Positive and linear correlation were observed during a calibration experiment between the Palpometer scale and actual applied forces. In their evaluation study on the palpation of three various objects which were different in shapes and materials (solid flat, solid sphere, and elastic rubber foam), a significantly higher force readouts for the elastic object were reported (Bendtsen et al., 1995). No significant variations in pressure intensities were reported in a control over force task neither for the day-to-day test (same person two different recordings with a week interval) nor in different tasks (same person two different tasks - palpation of temporal muscle and mastoid) when concurrent visual augmented feedback was provided. Finally, significant variation was reported between participants in palpation of temporal muscle and mastoid (different persons - different tasks) when no visual feedback was provided and these variations were paramount among inexperienced subjects. Women participants had the lowest force readings as compared to men.

In another study by Futarmal et al. (2011) a low-cost mechanical palpometer were used to facilitate the assessment of deep pain sensitivity in myofacial palpation. Clinicians were able to feel the tapering end of the mechanical rod when it was fully pressed. Three springs were used ($0.5, 1.0$, and $2.0\ kg$) to provide resistance against mechanical displacements of the rod inside the cylinder to provide different force levels (springs were calibrated by a digital force meter). (Futarmal et al., 2011) have reported a low test-retest variability with more accurate control on force when mechanical palpometers were provided.

Srinivasan and Chen (1993) have investigated the human ability in controlling normal forces and the impact of various augmented sensory feedback in aiding control performance. Three human subjects were asked to exert forces with their index fingertip on a force sensor while seated in a force tracking experiment. Target force-time profile was displayed at the beginning of each trial and participants were instructed to track the target force as close as possible. Local anaesthesia administered to the middle pallanx of the subject's index finger in a follow up experiment after at least two days, to block the tactile sensory information while in the first experiment under normal condition both tactile and kinaesthetic information were available to the subjects.

In constant force tracking tasks, visual feedback was provided under both normal and anaesthetised conditions and it was later withdrawn to repeat the tasks. In no visual feedback condition under both normal and anaesthetised situations, the experimenter has verbally signalled the participants when they were first reached to the target force level and then participants were supposed to hold that for 14 seconds. Absolute error (error = |desired - actual|) was computed for each constant force targets ($0.2N$ *to* $1.5N$ *in* $0.25N$ *steps*). Srinivasan and Chen (1993) have pointed out that magnitude of the error and its variations were affected by the absence of the visual feedback (under both normal and anaesthetised conditions) with respect to target force value whereas only the magnitude of error was affected by the absence of the tactile sensation.

## 3.3 Haptic-Enabled Virtual Reality in Medical Education

Recent advancements in haptic-enabled virtual and augmented reality simulation techniques had a great impact on learning motor skills particularly in medical education (Coles et al., 2011b). Physical involvement in virtual simulations which delivers more immersion, minimising the risk of putting patients' health in danger, and availability in early stages of the medical education are some of the advantages of this methods. However, huge design and development expenses, lack of simulation realism, feedback latency, and systematic evaluation of usability in most cases are stated as the existing drawbacks Dinsmore et al. (1997); Sigrist et al. (2013).

In a research study led by Dinsmore et al. (1997), a novel haptic-enabled virtual simulator were proposed to enhance the students' methodological and physiological understandings of subsurface tumour palpation training. Participants were divided into two a control group (90 seconds of training) and a training group (300 seconds of training) with different training durations in their familiarisation sessions. A 3D scene with two balls were given in the familiarisation trial and participants in both groups were asked to virtually palpate a red ball (hard tumour), a green ball (soft tumour), and the white background in the scene (liver tissue) to feel the different force profiles.

In their training trials, a segmented 3D model of a female torso was proposed to be adequate for liver palpation since the focus of training was on the abdominal region. Participants were able to see and navigate directly through the abdominal cavity during the examinations of the virtual patient. Six consecutive trials were provided in the same orders to the both groups with either one subsurface tumour or no tumour (two hard, two soft and two none). Force feedback was estimated by engineering techniques such as Finite Element Method (FEM) and it was delivered via a pneumatic haptic glove (Rutgers Master II).

Their training was followed by a short quiz in which participants were asked to indicate the location of each tumour by the index fingertip of a virtual hand model and to describe the compliance of the tumour(s) by typing "h" or "s" on the keyboard. Length of examination, localisation accuracy, and precision of identified compliances were recorded to evaluate palpation performances in a within and between subjects study.

No significant difference between groups were reported neither in localisation or type detection of the tumours. However, in within subjects evaluation the control group have shown significant performance in identification of hard tumours compare to soft ones. Dinsmore et al. (1997) have suggested that participants were able to detect hard tumours more likely because their force profiles were noticeably different from liver tissue. It was also concluded in their study that identification of subsurface tumour demands less training than the ability to distinguish hard and soft tumours.

## 3.4 Summary

Mechanical and physiological aspects of the human hands are reviewed in this chapter. Palpation metrics are identified with the help of medical experts and existing quantification studies were reviewed to select/design a nonintrusive measurement technique to collect palpation metrics without causing any interference during medical examination process. Finally, existing studies on application of haptic-enabled virtual simulations in medical educations were reviewed to highlight the impact of technological interventions in current medical curriculum.

# Chapter 4

# Research Methodology

## 4.1 Introduction

This chapter presents a technology-aided approach to enhance current abdominal palpation examination training and its assessment in medical education. A mixed-mode research methodology is used to predict the usability and usefulness of the proposed approach. This method is designed based on the current practice in medical curriculum (Patel and Morrissey, 2011) and it benefits over dedicated qualitative and quantitative studies throughout the research process. User-Centred Design (UCD) research methods were employed to ensure the new technology-aided training and assessment technique complies with the user and domain needs. In addition, this research benefits from active collaboration with medical experts and students throughout the design and evaluation process. A brief description of the most widely used UCD methods are outlined in section 4.2. The use of UCD methods in different stages of the research methodology and their predicted outcomes in each stage are presented in section 4.3. Finally, a summary is given at the end of this chapter.

## 4.2 Ergonomics Research Methods

Elicitation of user requirements (or extracting human factors) is a compulsory step to predict the aspects of usability and usefulness of a technique in human-centred research studies. This is crucial to understand the user and domain needs in health-care related studies and furthermore relates to additional challenges such as patient safety and ethical concerns (Martin et al., 2006). Therefore, the involvement of medical users (tutors and students) as an active part of this work throughout the research process (concept, design, and evaluation) conforms to literature recommendations (Vredenburg et al., 2002; Martin et al., 2006; Kitzinger, 1995). Thus, the UCD process model is used in this research to form a proper understanding of the requirements and to fulfil them throughout the design and evaluation processes.

In a survey by Martin et al. (2006) on the role of ergonomics (human-factors) in medical research studies, UCD methods were classified into two categories based on the purpose of use; exploratory or scoping methods and evaluation methods.

These methods are widely used in different ergonomics studies to identify and measure user and domain needs early in the study and to fulfil them throughout the process in order to achieve maximum effectiveness and efficiency. Furthermore, these methods were also reported as the most frequently used in non-medical research domains (Vredenburg et al., 2002). However, less structured methods such as low-fidelity prototyping and heuristics were also rated highly for their quick and cost-efficient advantages in the same study. A brief description of UCD methods are presented in this section followed by their advantages and drawbacks.

### 4.2.1 Ethnography

Ethnography is normally based on a long term in situ observation of processes and users to identify their potential deficiencies via interviews or documentation analysis. This might be through recording verbal and non verbal behaviour to form a comprehensive and detailed knowledge about the process. However, it is an extremely time consuming and costly method and for this reason is rarely used in medical domain.

### 4.2.2 Contextual Inquiry (CI)

Contextual Inquiry (CI) was introduced as a solution to counter address the challenges in ethnography. This method benefits from techniques such as shadowing and questionnaires to extract clinical needs. However, close observation of users on site may raise ethical concerns in healthcare studies. This method is based on collaboration between researcher and end-users to extract information that may not be recognised by the user as significant or important.

### 4.2.3 Focus Groups (FG)

Focus groups are very popular as a cost and time efficient method particularly in healthcare studies (Kitzinger, 1995). This method could be used in different stages of research to extract user requirements, to collect feedback on prototypes, and to be used in conjunction with other methods in the evaluation phase. Although, this method is a form of group interviews, the interaction between group members (group dynamics) could be more effective to explore participants' experiences and knowledge. The information extracted by this method is mentioned to be beyond the reach of other methods (Kitzinger, 1995). One benefit of this method is that the group dynamics could lead the discussion towards taboo topics. However, fear of punishment (eg. loosing their job) could also silence individuals. Another advantage of focus groups is the role of the end-user as an active part of the process which is highly demanded in human-centred studies.

### 4.2.4 Usability Test (UT)

Usability tests are vital in ergonomics studies to evaluate the effectiveness and efficiency of a new technique or concept while it is employed by end-users in a real-world practice. In addition, the strengths and weaknesses of a new learning technique could be explored by this method. Various data collection methods such as qualitative (via observations, interviews or questionnaires) and quantitative (via quantification studies) could be employed to collect information. However, this method is only ideal to reveal functional problems and it is recommended to be used in conjunction with other methods which are effective to identify contextual problems within processes such as Focus Groups (Martin et al., 2006) .

### 4.2.5 Cognitive Walktrough (CW)

This method is used when access to the end-user is restricted by their domain of study such as healthcare. In this case other alternatives are used to mimic the end-users behaviour within design process. These proxies could be selected from research team or other users within the target domain. For instance, a clinician could roughly explain the patient's needs but this could be very hard specifically for a novice without enough knowledge to act as the end-user. This method is suggested to be used as a preliminary test to identify early problems in design (e.g. evaluation of an early prototype) before a proper usability test (Martin et al., 2006).

## 4.3 Research Method

UCD methods were used in different parts of this research to ensure that the proposed methodology aligns with educational objectives in medical school. A structured programme is proposed by Patel and Morrissey (2011) to shift clinical skills acquisitions from clinical settings into the early stages of medical education. This programme is comprised of the following steps:

- ***Understanding:*** to realise importance of learning clinical skills and anatomical and physiological principles
- ***Observational Learning:*** to observe verbal instructions and physical demonstrations of skills by medical tutors
- ***Practice and Assessment:*** to perform frequent rehearsals, self-assessment and assessment by tutors, and constructive feedback on competency
- ***Certification:*** to receive approval from tutors as safe and competent

This research intends to propose a comprehensive methodology through the elucidation of domain requirements from the first two steps in current medical education to enhance the third step with an innovative technology-aided training and assessment technique. Appropriate UCD methods were selected in different stages of this research to form a multidisciplinary team in order to design and evaluate the effectiveness and efficiency of this technique. Figure 4.1 illustrates a step-by-step design of this research methodology.

Students in first year of medical education are selected as the target population in this research to help shift the skills acquisitions process into the early

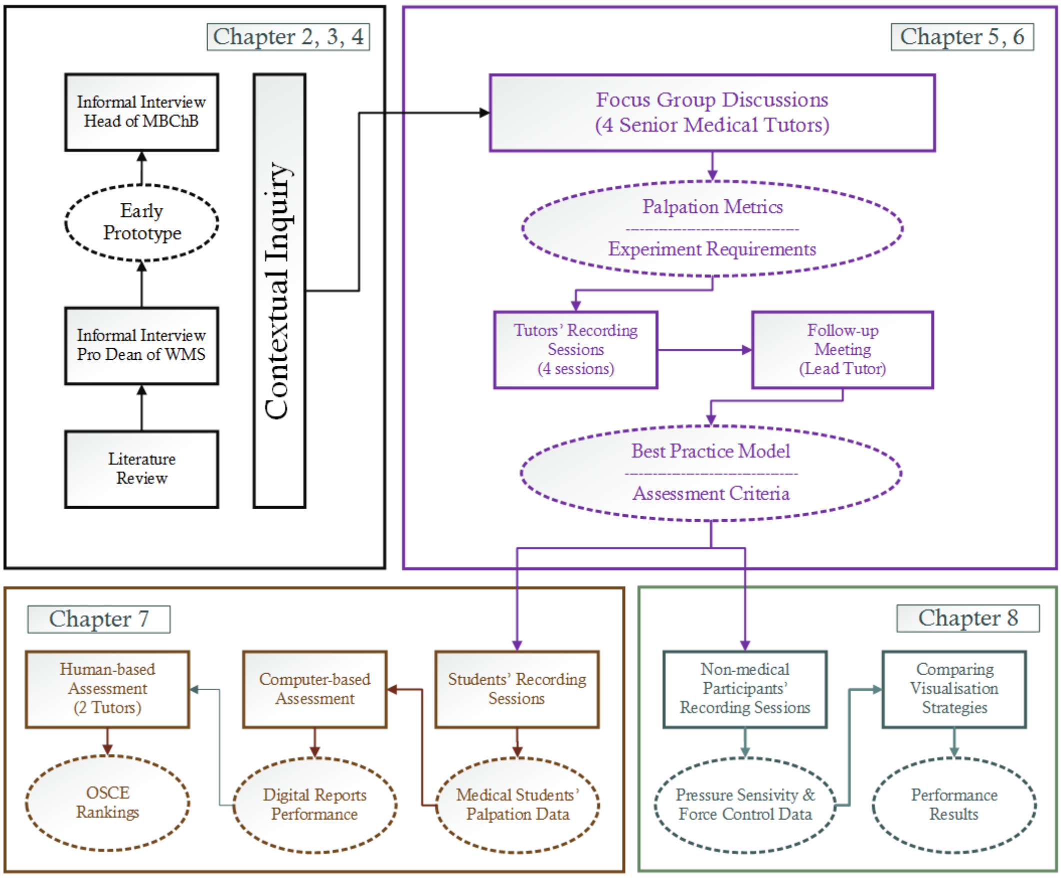



Figure 4.1: Research Methodology - procedures are presented by solid rectangles and predicted outcomes are illustrated by dashed ellipses

years of their study. This is important for medical schools based on our informal interviews with head of the undergraduate program to provide a realistic training to the actual practice in early years to enhance the competency but ethical challenges such as patient safety prevents practice with real patient. This in turn shortens the learning time-span and frequent rehearsals lengthen the retention period. Both qualitative and quantitative data have been collected within different stages of this research via a mixture of UCD methods to introduce a robust and reliable training and assessment technique and to evaluate its impact on medical education. In the following section, different stages of this research methodology are briefly discussed followed by detailed description of each stage in its representative chapter.

### 4.3.1 Informal Meeting

This research began with an extensive review on existing teaching resources (e.g. literature-journal articles, medical textbooks, and multimedia resources) in medical education in order to identify all types of physical examinations in which dexterous hands-on interactions are required to diagnose diseases. An informal session was planned early on this research to meet Pro Dean of the Warwick Medical School (WMS) to narrow down the vast domain of physical examinations to a few of the most challenging ones.

Abdominal palpation examination was suggested in this meeting since it was reported as a very difficult task to perform by the medical students. Anatomical complexity of the human abdominal organs was suggested by the medical experts as an important challenge in teaching palpation skills. In addition, the concept of a technology-aided quantification method with real-time feedback on competency was proposed in this meeting while it was suggested by several studies in existing literature(see chapter 2 and 3). The idea was supported by the medical expert as a beneficial approach to enhance conventional abdominal palpation examination training and its assessment process.

### 4.3.2 Understanding the Principles

As noted already in the previous chapter, the existing quantification studies in abdominal palpation examinations were reviewed to explore their key features and to use them as a guideline for this research. Although one can get an idea of the skills acquisition steps for abdominal palpation examinations from the literature, it is still essential to participate in a formal training session to understand the potential complexities which may occur within teaching, learning and assessment processes. However, due to a lack of ethics approval in early stages of this research, online digital teaching resources (e.g. videos of formal palpation examination sessions) were observed as part of the Contextual Inquiry (CI) method. This method was beneficial to form a preliminary understanding of the anatomical and biomechanical aspects of the hands-on practice during the palpation examination process.

### 4.3.3 Prototyping the Educational Interface

As noted earlier in chapter 3, design of an early prototype for palpation training was planned due to a lack of available off-the-shelf measurement interfaces with the flexibility required for this research. Moreover, additional factors such as budget restrictions and time commitments were influential in making this decision. The Cognitive Walkthrough (CW) method was used to evaluate the early prototype, when an end-user is not available with the help of proxies (e.g fellow colleagues) to ensure it complies with the domain principles which were extracted via literature reviews and process observations.

This prototype was made to demonstrate the concept of a technology-aided training and assessment method presented in the next stage of this research. The early version of the prototype was evaluated by a team of medical tutors in focus group sessions as part of usability test to obtain feedback and list of design refinements before data collection phases. This stage is fully described in the next chapter.

### 4.3.4 Exploration of Study Requirements

In a follow up communication with the Pro Dean of the WMS, head of the MBChB programme (Bachelor of Medicine, Bachelor of Surgery) was introduced to the research investigator and an informal meeting was scheduled with him to present the research progress and to plan for future collaborations. The main intention of this meeting was to identify a team of medical experts who teach physical examinations in current curriculum.

The Focus Group (FG) method was used to properly understand the domain, to extract experiences via discussions between colleagues and to identify current challenges in the abdominal palpation examinations educational process. This research follows the characteristics of ideal FG practice that are described by Kitzinger (1995). User and task requirements were identified and transcribed in the form of meeting protocols (or minutes) from verbal discussions and written answers in the tutors' questionnaire as part of the self-reporting technique. These requirements are briefly described below.

#### 4.3.4.1 User Requirements

In a survey on new directions for Human Computer Interaction research (Rogers, 2009), *Understanding* of human values (ergonomics) is proposed as a new step in the conventional user-centred research and design model (*Study, Design, Build, Evaluate*). Therefore, user requirements were outlined by medical users in a series of FG sessions. Four medical experts who teach palpation tasks in Warwick medical school were invited by the head of the undergraduate programme in medicine (MBChB) to take part. The research aims and objectives were presented briefly by the research investigator and the early prototype was given to them for initial evaluation. A seat back strategy (collecting data by listening to the group discussions) was taken by the research investigator to let the medical experts to elaborate key requirements for future steps. The potential of research in medical education and initial requirements were collected via open-ended questions (see appendix A.2) and carefully noted from their discussion. Thus, the following requirements were identified by the medical experts:

- ***Motivation*** - the abdominal palpation task was described by medical tutors in this study as 'difficult to learn' task due to its anatomical complexity which sometimes causes frustration for both tutors and students. Hence, a technology-aided training tool based on a robust quantification study is addressed by the people filling out questionnaires as very helpful to enhance learning experience.

- ***Complementary Method*** - the role of medical tutors in conventional medical training is undeniable and could not be replaced. Hence, technology-aided interventions should be used in conjunction with the current practice in the medical curriculum.

- ***User-friendly Design*** - The new training and assessment technique must be easy to understand and simple to use for medical users to enhance the usability of the new technique. Operational complexity could decrease the medical users' motivation to adopt the contemporary training and assessment approach.

- ***Unintrusive Design*** - the interface must provide a similar experience to the real-world experience without any interference in the palpation process.

- ***Real-time Feedback and Instant Assessment*** - Instant feedback on competency is highly demanded during the learning phase. Also, an instant report on students' overall performance could enhance the existing assessment process.

- ***Health and Safety*** - since any wearable technology is in direct contact with human skin, constant use by different medical users on several patients may result in skin infections. Also, an electrostatic shock could occur and it could put the patient's safety at risk. In addition, exhaustion caused by the measurement interface in quantification studies could directly affect the user's competency and experience.

- ***Time and cost*** - these are often identified as the two paramount challenges in the adaptation of a new technology-aided intervention in current medical education.

#### 4.3.4.2 Task Requirements

The task requirements were also determined in a follow up FG session with the help of medical tutors soon after the user requirements were satisfied by the measurement technique. Three abdominal palpation examination tasks were selected to explore two important learning objectives; to highlight the transition between applied forces and to illustrate the correct formation of the palpating hand by localisation of the applied forces. These tasks were defined by medical tutors as follows:

- Superficial Palpation (gentle palpation, less pressure)
- Deep Palpation (more pressure)
- Palpation of the liver (locate specific organ)

Also, palpation of four quadrants with right hand was declared by the medical tutors to minimise variations caused by employment of different techniques for superficial and deep palpation tasks. Actor patients were invited from two genders with three different anatomical variations to ensure the measurements are reliable and robust. Figure 4.2 shows the task requirements that are identified by the medical tutors in group interviews.

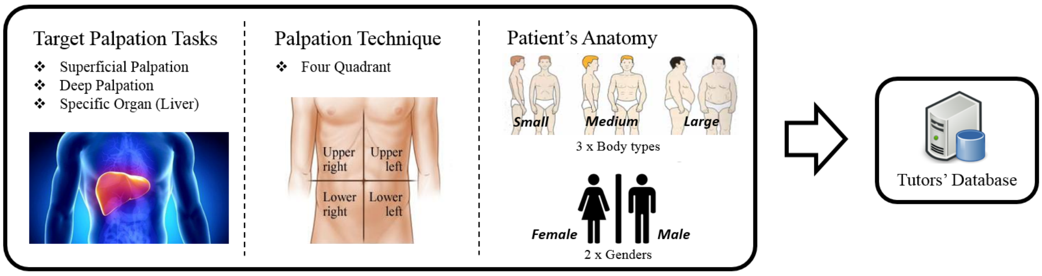



Figure 4.2: Task requirements

### 4.3.5 Creation of the Best Practice Model

The knowledge of the dexterous use of the human hands within abdominal palpation examinations is usually transferred from masters to novices via lifelong rehearsals of clinical skills (Patel and Morrissey, 2011; Macleod et al., 2009). Thus, it is essential to model the medical tutors' palpation skills via a novel quantification technique in order to establish a ground-truth reference. The existence of such a reference model is crucial in the evaluation stage of this research to ensure all students are going to be assessed exactly the same. Palpation metrics (position, orientation, pressure) were collected via an innovative measurement interface from the medical tutors' sessions. However, in this research we focus on applied pressures at different regions of the human hands were analysed and employed in the evaluation study. Chapter 6 presents detailed overview on ground truth exploration stage and the potential findings from tutors' performances.

### 4.3.6 Evaluation Study

The Usability Test (UT) method is used in the final stage of this research to evaluate if the proposed method can fulfil its potentials in learning complex motor skills. The impact of real-time multimodal feedback of applied forces on the medical students' competency was assessed by this experiment. Consequently, a digital competency report is provided to evaluate its benefits in the medical tutors assessment process. Therefore, a pilot study was scheduled in the last focus group session to employ this technology-aided training and assessment technique in one of the students formal training sessions to evaluate its usability and usefulness in a real-world practice. Quantitative measurements were collected from students' performances to be compared with the best practice model which is described in depth in chapter 6 for each abdominal palpation task during the assessment process. In addition, quantitative data were collected from students who had had a chance to learn abdominal palpation skills with the new technique via usability feedback forms. This stage of the research is presented in chapter 7.

### 4.3.7 Towards Game-based Training

The fun factor behind computer games is a key motivation for learners to engage and immerse in learning process. As the last part of this research it was our ambition to investigate the application of serious games in motor learning and to compare it with other visualisation strategies that were employed in the evaluation study (eg. abstract visualisation).

## 4.4 Summary

This research intends to comply with the principle requirements of the abdominal palpation examination skills acquisitions steps. User-Centred Design methods and their potentials in quantification studies were introduced in this chapter. Moreover, the appropriateness of these methods and the advantages and disadvantages of them were further discussed to highlight potential uses of each method in research methodology. Finally, different stages of the research methodology design are presented in this chapter and the predicted outcomes of each stage are explored.

# Chapter 5

# The Measurement Interface

This chapter presents a general overview of the measurement interface which has been designed and prototyped with the help of medical experts to enhance conventional abdominal palpation examination training and its assessment. A short description on technological aspects of the measurement interface is provided only to educate the readers about the general features, since the intention of this research is to evaluate the impact of a new technological method rather than introducing a new product. Active involvement of the medical experts in design and prototyping process, use of recommended design strategies in literature (eg. multimudal display, common metaphors), and robustness and reliability evaluation via a calibration study are the key contributions to knowledge. These information could be used as a guideline by researchers who are studying the human hands' ergonomics.

## 5.1 Current state of the art

Current state of the art in ergonomic studies were extensively reviewed to identify potential measurement interfaces that are used in similar research studies. Commercial wearable interfaces for quantification of force exertion by the human hands were investigated to form a taxonomy table to highlight their strengths and weaknesses. Table 5.1 shows the commercially available technologies early on this work.

Extreme price per units (eg. extra charges for software and more sensors), long calibration processes, lack of flexibility in design, poor coverage, and bulkiness are some of the disadvantages of the existing commercial quantification tools. Moreover, majority of the commercial products are manufactured without active involvement of the end-users due to their generic designs. Thus, an innovative low-cost measurement interface is designed and developed with guidance of medical experts to satisfy all of the study requirements.

Table 5.1: Taxonomy of the commercial pressure mapping systems (Aug 2012)

| ***Name*** | | Grip™ System | FingerTPS II™ | NEX-GS-24 | SensoGlove | ergoGlove™ |
|---|---|---|---|---|---|---|
| ***Vendor*** | | TekScan | Pressure Profile Systems (PPS) | NexGen Ergonomics | SensoGlove | Mobility Solutions |
| ***Applications*** | | Ergonomics<br>Improved product design<br>Sports applications<br>Robotics | Ergonomics<br>Medical applications | Hand-tool analysis<br>Design and research<br>Medical applications | Golf club grip | Testing equipment |
| ***Force Measurement*** | | Area-based | Point-based | Point-based | Point-based | Point-based |
| ***Sensors' Type*** | | Resistive Matrix-Mode | Capacitive | Fabric sensors (ISS sensors) | Force Sensitive Resistors (FSR) | Force Sensitive Resistors (FSR) |
| ***Coverage*** | ***Fingers*** | Full | Full | Full | Partial | Partial |
| | ***Palmar*** | Full | One | Full | No | No |
| | ***Radial Border*** | No | No | No | No | No |
| ***On-board Tracking*** | | No | No | No | No | No |
| ***Basic Model*** | | 19 Pads | 2 | 20 | 4 | 4 |
| ***Connectivity*** | | Wired or Wireless (RF) | Wireless (BT) | Wired or Wireless (BT) | Stand-alone | Wired (USB) |
| ***Weakness*** | | Bulkiness | Cost, Calibration | Accuracy | Customisability, Accuracy | Coverage, Higher ranges |
| ***Price*** | | N/A | £6,220 | £4,500 | £60 | £3,198 |

## 5.2 Design

A comprehensive pipeline was designed for an ideal palpation measurement interface to address particular user and task requirements in this domain. As noted already in chapter 3 (exploration of study requirement) these requirements were extracted by reviewing the current literature on quantification studies in healthcare and from the focus group sessions with help of the medical tutors. Hereafter, this measurement interface pipeline is referred to as Pressure And Rotational Sensory Motion Capturing (ParsMoCap). In addition, an accurate calibration method is proposed at the end of this chapter to provide a guideline for future researchers in this field. Figure 5.1 shows the ParsMoCap and its outcomes in different stages of this research.

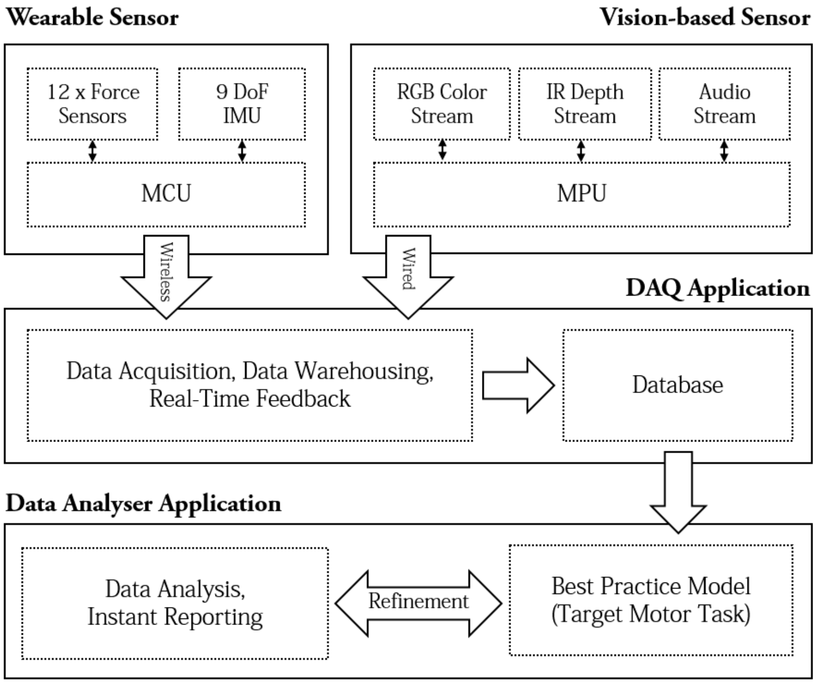



Figure 5.1: ParsMoCap system block diagram

### 5.2.1 Multidisciplinary Design Team

Four medical tutors who teach abdominal palpation examination skills in Warwick Medical School (WMS) were invited to take part in this research. An early version of the measurement interface was evaluated by each member during the first focus group session and design refinements were summarised by the interaction between the medical tutors. One tutor who currently teaches abdominal palpation skills in WMS was invited in a series of follow up meetings throughout the iterative design process, to advise the research investigator on detection of potential patterns and knowledge from the captured data from medical tutors, data visualisation and further analysis. The medical tutors' feedback in design stage was crucial to create assessment criteria and to generate competency reports prior to the evaluation study.

### 5.2.2 The Interface Framework

This section presents a brief overview on each component of the ParsMoCap interface which is used in this research to capture abdominal palpation metrics from human participants.

#### 5.2.2.1 Pressure

A common technological challenge in force quantification studies to measure applied forces during hands-on interactions is the installation of the transducers (e.g. force sensors) on such an articulated structure (the human hands) without decreasing dexterity (Jensen et al., 1991a). One possible solution to this problem is to identify a series of contact points on the human hand for particular interactions. These contact points are used as a reference to mount force-sensing transducers with smaller spatial resolution to enhance the flexibility of the hands.

Thus, twelve contact points were identified on the right hand's palmar surface and its radial border of the index finger, based on advice given by the medical tutors in the user requirements elicitation phase. These points were identified during live demonstrations of target abdominal palpation tasks (superficial, deep, and liver edge) on a dummy mannequin with the initial prototype of the ParsGlove. Figure 5.8 shows the contact points' positions on the right hand as the palpating hand, for all three tasks.

#### 5.2.2.2 Orientation

Another important metric to be measured during the abdominal palpation examination process is the rotational movements of the palpating hand in space. The following rotational movements are stated in medical and bio-mechanical domains (Bunnell, 1964; Taylor and Schwarz, 1995) for the human hands with wrist as pivot point.

- Pronation/Supernation (Roll around X axis)
- Flexion/Extension (Pitch around Y axis)
- Dorsal/Ulnar Rotation (Yaw around Z axis)

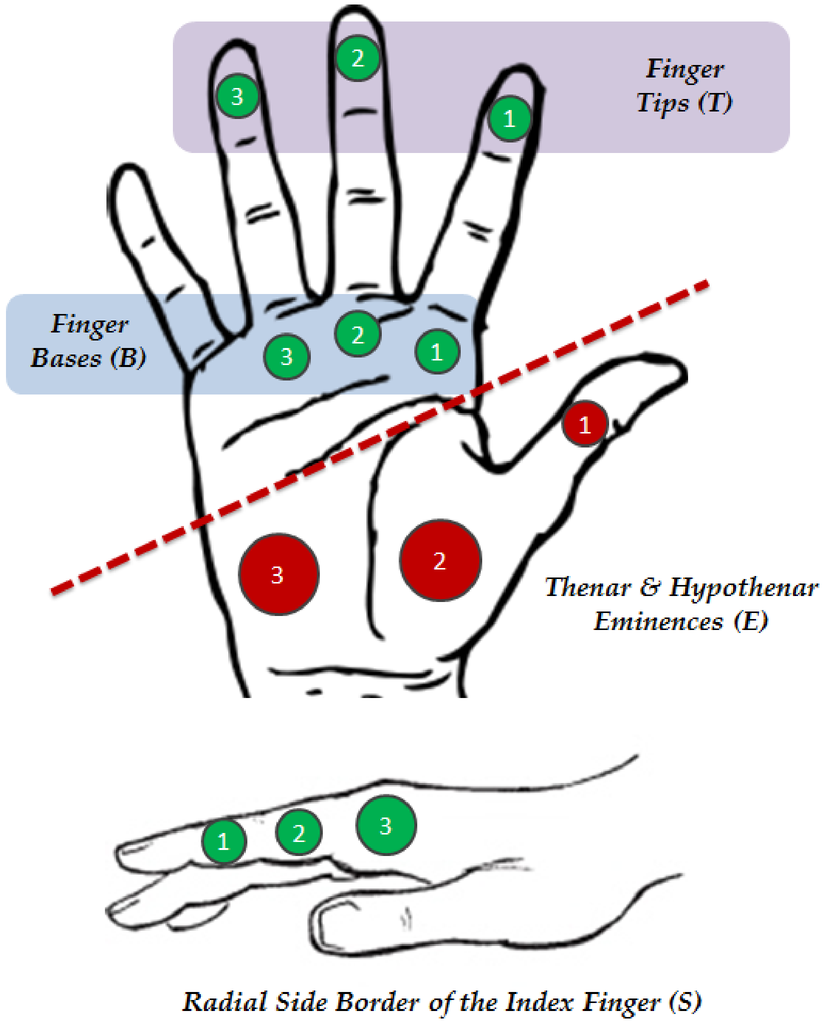



Figure 5.2: Contact points on the palpating hand's surface

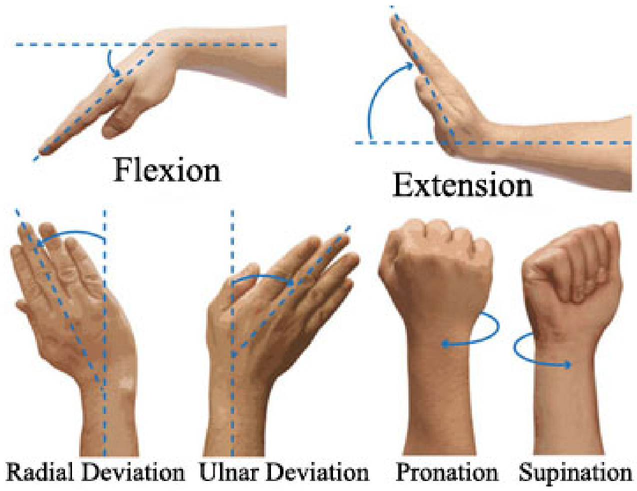



Figure 5.3: Orientation mapping metrics. Image courtesy of (Morphopedics, 2015)

In order to account for all useful orientations, a wearable sensory quantification technique is proposed as part of the ParsMoCap interface to measure applied pressures as well as the rotational movements of the human hand during palpation process. Figure 5.4 shows the ParsGlove which is designed and prototyped based on the feedback from the medical tutors.

Figure 5.4: ParsGlove is the wearable sensory input with color markers to capture applied forces, rotational movements and spatial position of the human hand

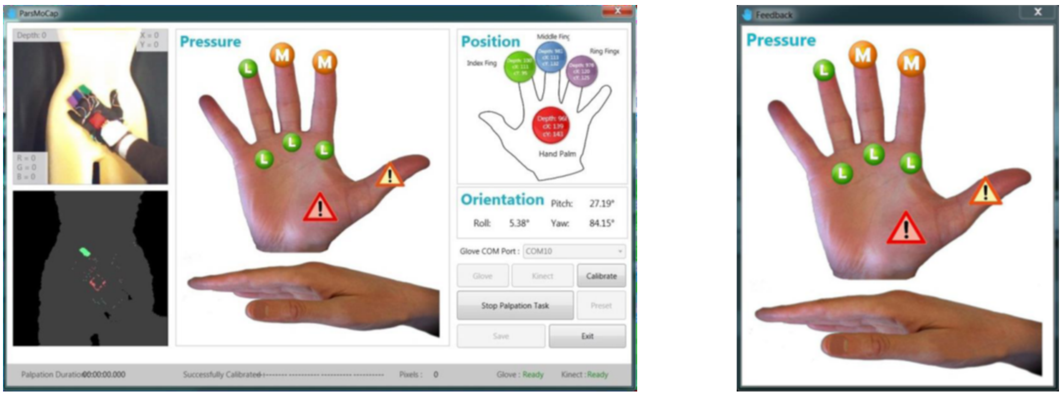
The force and orientation metrics were digitally sampled by an on-board micro-controller chip and the raw data has been transmitted from ParsGlove to the base computer via a wireless solution to provide freehand interactions in a non-intrusive fashion.

#### 5.2.2.3 Position

The position tracking techniques are highly influenced by the resolution of the target tracking area on the human anatomy. Vision-based tracking techniques were surveyed to identify the best approach which complies with the user requirements in this research. In general Vision-based tracking methods are divided into two categories; marker-based and marker-less. A marker-based tracking method, comprised of four colour markers, is used to capture global (palmar) and local (fingers) movements of the human hands since a wearable sensory input is already introduced to capture other metrics. Colour Markers were attached to the ParsGlove on areas which were defined by the medical tutors. A Kinect sensor was mounted on top of the patient's body and was focused on the abdominal region to detect the markers and return three dimensional values to represent position of each marker in space.

#### 5.2.2.4 Data Acquisition

The data acquisition user interface is comprised of two panels. The main panel (*Monitoring Panel*) monitors the data collection process and an auxiliary panel (*Feedback panel*) provides visual feedback on applied pressures on patient's abdomen by the medical user (locations and magnitudes). Figure 5.5 shows the monitoring and feedback panels.




(a) Monitoring Panel

(b) Feedback panel

Figure 5.5: Data Acquisition User Interface

Different force magnitudes are represented by three colour-coded symbols ranging from small (green), medium (amber) and high (red) based on the information extracted from the tutors' best practice model.

#### 5.2.2.5 Data Analysis

The data analysis user interface (hereafter known as Examogram) was designed, based on the design requirements that were explored in series of meetings with one of the medical tutors. These included the ability to perform preliminary analysis such as frequency of presses per task, the highest recorded pressure per press, and the duration of each press on tutors' datasets to create a ground truth model. Examogram was also used to perform similar statistical analysis and generate digital competency reports on the medical students' datasets. These outcomes were used to compare the students' competency against the proposed best practice model as part of the competency assessment process.

## 5.3 Calibration of the Force Sensors

Piezoresistive Force Sensitive Resistors (FSR) are widely used in ergonomics studies (Jensen et al., 1991b; Williams et al., 2012b,b) to measure magnitude of applied forces by different parts of the human body. Low-cost per unit, simplicity in calibration, ease of use and their availability in different shapes and sizes and close to linear behaviour in lower force ranges are some of the advantages of the FSR sensors. FSR sensors' measurement range are highly affected by their circuitry interfacing method. Figure 5.6 shows the schematic suggested by the manufacturer for interfacing these sensors.

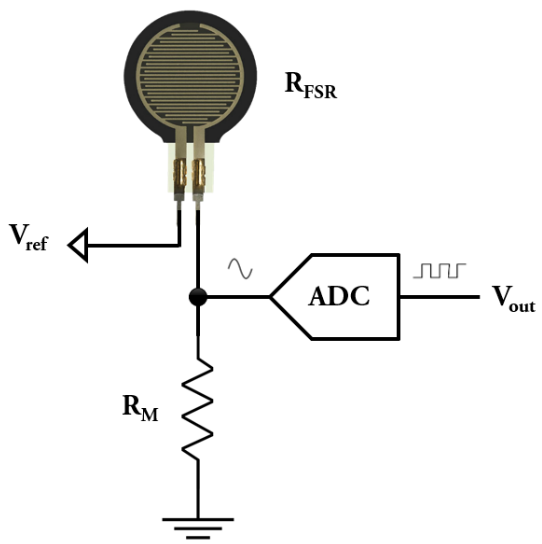



Figure 5.6: FSR sensors' suggested circuitry schematic

The electrical resistance ($R_{FSR}$) of the conductive material which is used in these type of sensors decreases by increasing the applied forces on the sensor's active area. This resistance is an infinite value in absence of forces and decays to zero when the maximum measurable load is applied which varies between models (eg. 100 Newtons). A two-wire communication is suggested by the manufacturer: one to supply a reference voltage ($V_{ref}$) (either 5 or 3.3 Volts) and, one to read the output voltage ($V_{out}$). A measuring resistor ($R_M$) is also used in the sensor's output circuit to limit the current and to enhance the sensitivity range. The output voltage is computed from equation 5.1.

$$V_{out} = V_{ref} \times \frac{R_M}{R_{FSR} + R_M} \tag{5.1}$$

The voltage-to-force conversion equation (rarely provided), uses this value to estimate the force. However, since the manufacturer's equation is highly influenced by laboratory test constraints, a more accurate calibration method is proposed to estimate the applied force values from the collected samples.

A digital force gauge measurement instrument (*Sauter* $FH-500$) with a dynamic measurement range of 0 to 500 Newtons was used to map the sensors' digital output during sampling process to an accurate numerical force value (Sauter GmbH, 2015). The device was mounted on a test stand with an adjustable lever to change the applied forced on the sensors detection area by mechanical displacement of the measurement instrument. Figure 5.7 shows the calibration interfaces which are used in this phase.

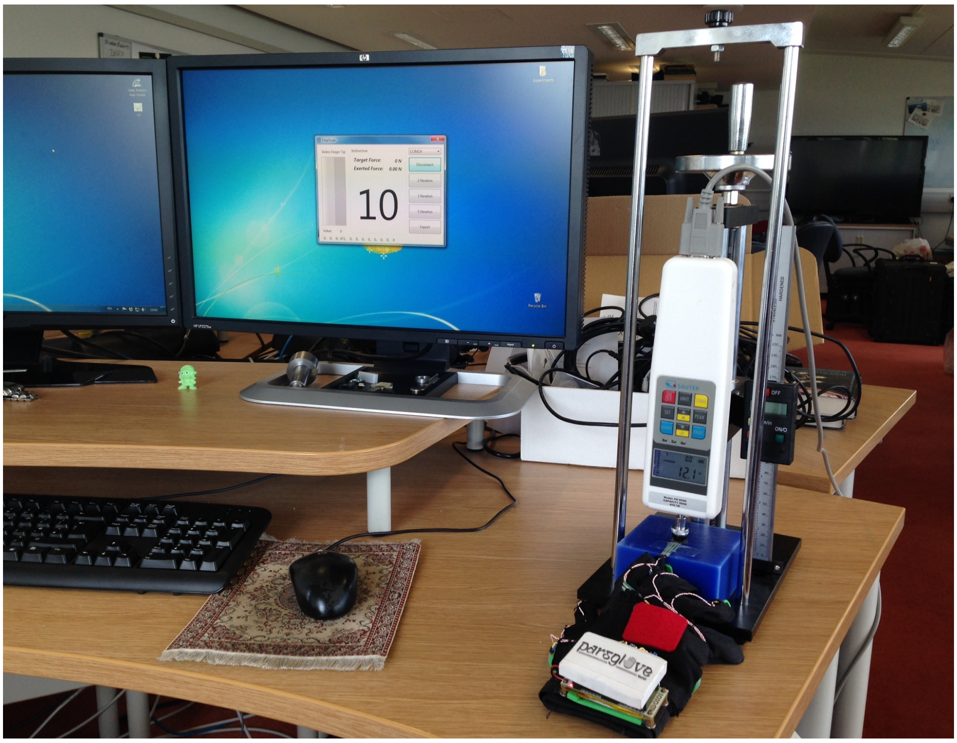



Figure 5.7: Calibration Interface - *Sauter* $FH-500$ for actual force value, ParsGlove and DigiScale for digital force value

Round-shaped FSR sensors (see figure 5.9) were used in three variety of sizes (small, medium, and large) with respect to the mounting position on the human hand. These locations were identified with guidance of the medical experts in R&D stage of our previous experiment. Five sensors were randomly chosen from small and medium size categories for the calibration phase to monitor the sensors' behaviour by changing the applied forces on their detection area. The large sensors where not included in calibration stage since they were only used to indicate the presence or absence of the force exertion on palmar surface of the human hand. Medical students are continuously advised to avoid leaning on the patient's body with this area during palpation procedure to avoid any discomfort. Figure 5.8 illustrates the thenar and hypothenar eminences on the palmar surface of the human hand.

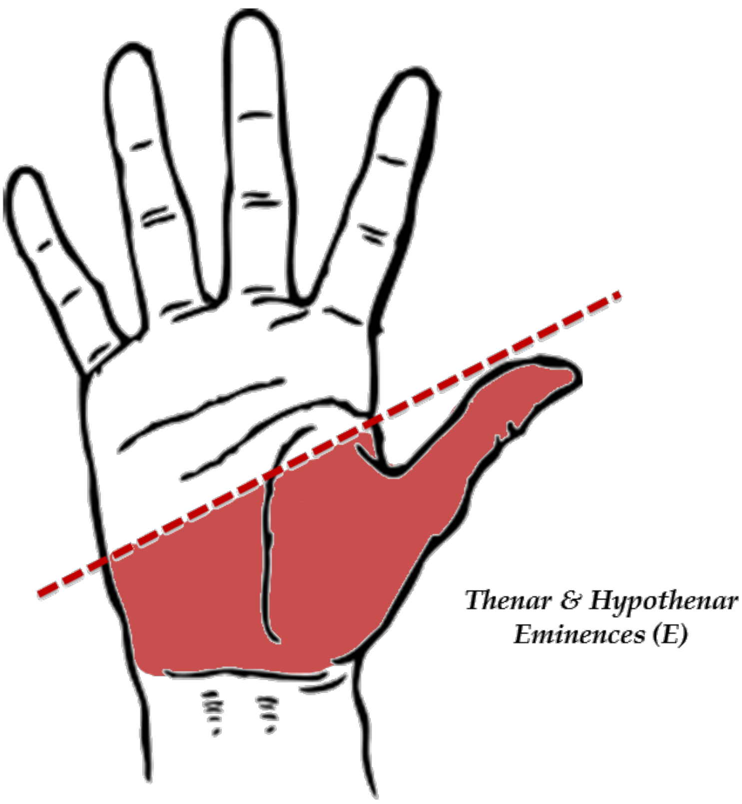



Figure 5.8: Contact points on the palpating hand's surface

The sensors' output voltages (0 to 5 Volts) were sampled into digital numerical values ($0 - 1023$ as one byte of data) by on-board Analogue-to-Digital (ADC block in figure 5.6) converting modules. The actual force magnitudes (in *Newtons*) were simultaneously recorded from the force sensors by a calibration test tool (Sauter GmbH, 2015) in each force application step. The sensors' digital output was increased by 50 arbitrary units in each calibration step until small changes on the digital output shows significant force readings (550 units for small and 750 units for medium sensors).

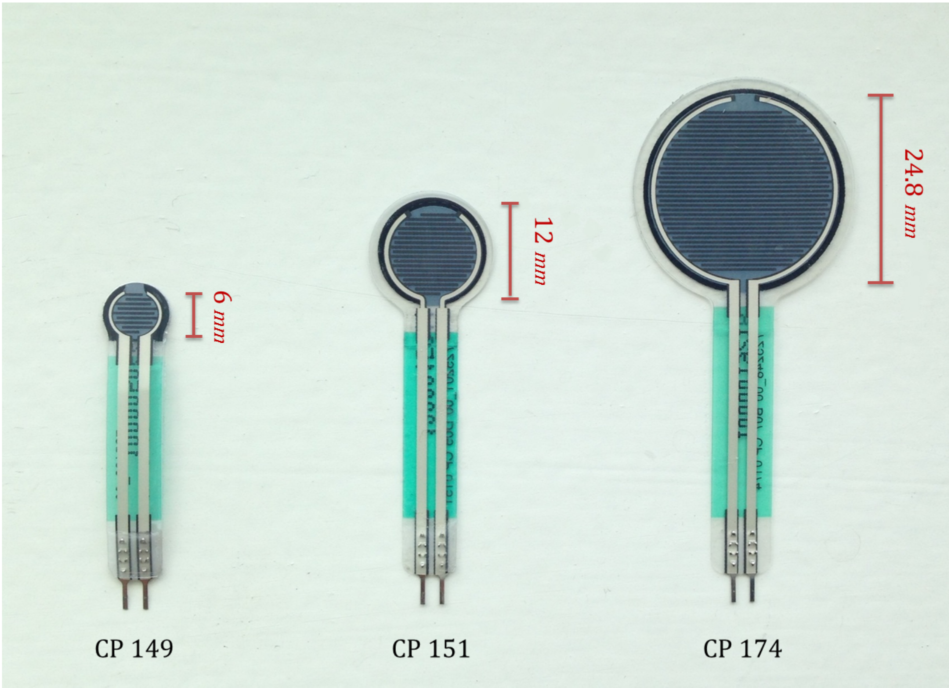



Figure 5.9: IEE round-shaped FSR sensors; small ($6mm$), medium ($12mm$), large ($24.8mm$)

Despite the noted advantages of the FSR sensors their force measurement reliability is highly dependant on application time. Two undesired behaviours are well described when time is considered in a calibration experiment (Florez et al., 2010). The first phenomenon is known as ***Creep*** which is caused by the reduction in sensors' electrical resistance after long term application of static forces (approximately 2 Newtons higher than the actual force value after 10 minutes). The second is ***Hysteresis*** reported as the loading and unloading curves (voltage-time plot) were not overlapped. The use of an epoxy resin dome on the sensors' active area is addressed to increase its pressure sensitivity. However, the force measurement range was significantly different when a dome is used particularly when sensors are mounted on the human hand. This may also reduce the human hands' pressure sensitivity and flexibility of the sensors' active area. The loading curve was monitored in this study when participants were asked to reach a given target force, hence, the occurrence of hysteresis was not considered. Also, the total force application duration was identified as 10 seconds; this helps avoid the behaviour of creep.

The force was loaded for a short period of time (approximately 5 seconds based on our previously captured data from medical experiment) to mimic a hand press-release action (see figure 5.10) and was released from the sensor's detection area soon after each calibration step to avoid appearance of creep and hysteresis effects.

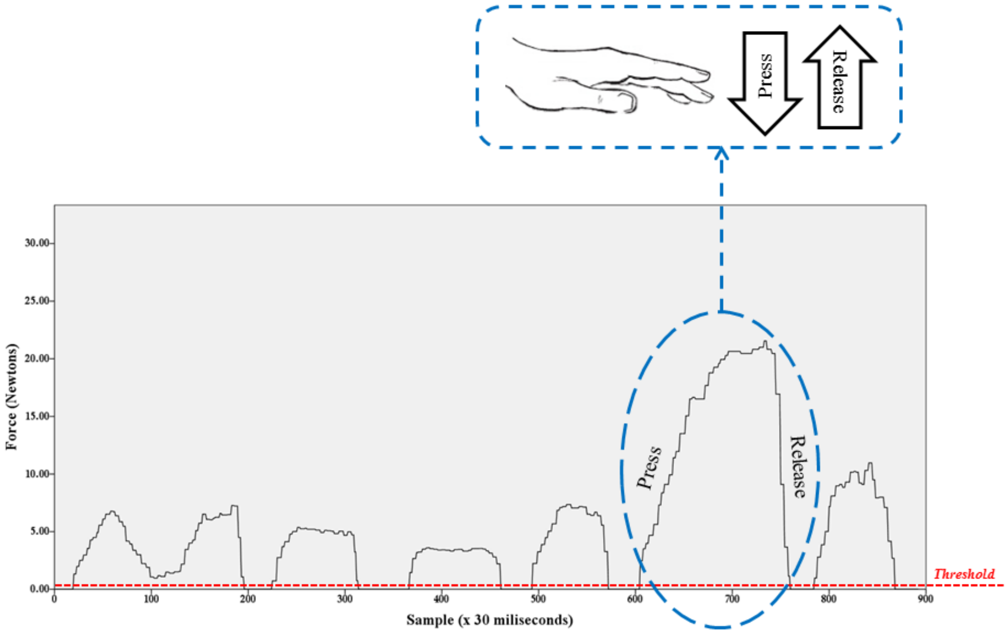



Figure 5.10: Press-release actions during abdominal palpation examination

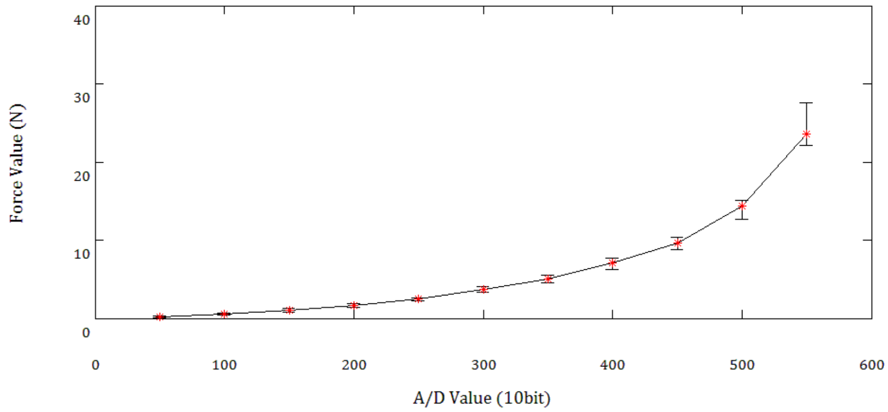
Finally, the sensors' calibration data were plotted (see figure 5.11) to illustrate the best force estimation (red asterisks) in each step and the potential variations among identical sensors (whiskers). Figure 5.11 shows the calibration outcomes for each category of sensors.

A $5^{th}$ degree polynomial equation (see equation 5.2) was calculated from the calibration data by curve fitting technique to accurately estimate the actual forces $F(V)$ applied by the medical users from the sensors' output voltages $V$ that are digitally sampled by the ADC module (0 to 1023).

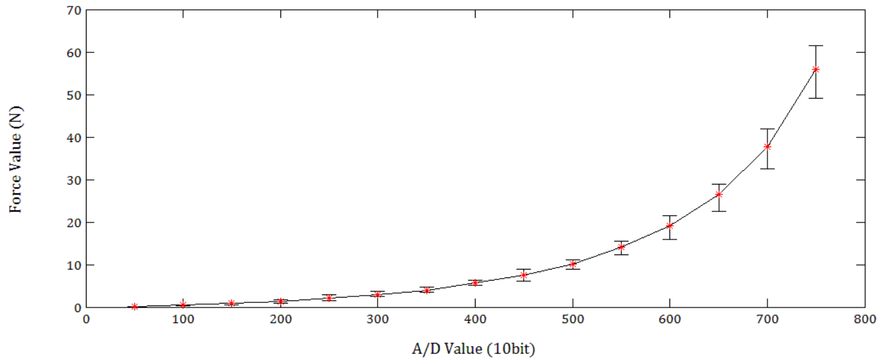
$$F(V) = c_5V^5 + c_4V^4 + c_3V^3 + c_2V^2 + c_1V + c_0 \tag{5.2}$$

## 5.4 Summary

A brief overview of the ParsMoCap interface, which was designed and prototyped with help of the medical collaborators, and used as a crucial part of this quantification research, is proposed in this chapter. In addition, a robust method for calibra-




(a) small size sensors' calibration results




(b) medium size sensors' calibration results

Figure 5.11: Calibration results for five randomly tested force sensors per type

tion of force sensors has been proposed to provide a guide for future researchers to validate data reliability. The results in the calibration stage revealed the extreme variations (more than 10 Newtons) between identical sensors when heavy loads are applied on the sensors' surfaces. The reliability of these sensors could also drop when a load is applied on them for long period of time. However, as stated in chapter 3 the durations of the press-release action in the target abdominal palpation examination tasks are below this threshold. In the next chapter, the proposed measurement technique is used to create a ground truth model for the target abdominal palpation tasks with help of the medical experts. Medical students' learning progress were evaluated with help of this technique in chapter 7 as compared to the developed gold standard model.

# Chapter 6

# Ground Truth Exploration

## 6.1 Design

As noted in the previous chapter four medical tutors who are experienced in teaching abdominal palpation examination skills in WMS were invited to take part in this research. A theoretical sampling method is used to identify current challenges in the abdominal palpation training process and to generate key concepts via observations and a series of open-ended questions. Group members were selected from the same hierarchical position to avoid silence or ignorance of the comments because of the fear of punishment from seniors. The tutors each with different medical specialities were invited to explore different perspectives on similar subjects. Three abdominal palpation tasks (superficial, deep, and liver) were chosen by medical tutors to investigate various aspects of abdominal palpation examination in hands-on practice. Superficial and Deep palpations were chosen to study on transition of force application from soft and moderate press to much harder presses in deep. Liver palpation was selected to evaluate correct formation of the hand and application of force only by specific part of the hand (radial border, index fingertip and index finger base). The interface capabilities were demonstrated to all tutors by the research investigator prior to the tutors' data collection session. A list of minor modifications were suggested by the medical tutors in the initial research and design meeting. The measurement interface and its software applications were reviewed based on this list to apply necessary changes. Also, a female chaperone monitored male doctors during female examination sessions.

Moreover, potential risks in measurement outcomes were discussed in a series of meeting before data collection session in this stage. Anatomical variations between actor patients and employment of different techniques despite the existence of a guideline were suggested risky factors. Thus, three different body types in two genders were invited to take part in this study. Also, an averaging method with help of the medical tutors was employed to resolve the variations.

## 6.2 Materials

The ParsMoCap application is used to capture three important parameters from the medical tutors. A TFT display was positioned in front of the research investigator to let him monitor the data collection process but no visual feedback was provided to the tutors or to the participants.

The Examogram application is used to analyse the medical tutors' raw data. The analysis results were used to develop a ground-truth model for each palpation task which were viral for the evaluation experiment in the next chapter.

The mattress was covered with a disposable couch roll for each participant and a medically approved hand sanitiser gel was provided as well as ultra thin powder coated polyvinyl gloves to be used inside the wearable interface to meet hygiene and safety requirements.

## 6.3 Participants

Four senior medical tutors were introduced and invited after the initial meeting with the head of the Warwick Medical School (WMS) Bachelor of Medicine programme (MBChB) , two of which are currently teaching clinical examination. The medical professional team were comprised of three male and one female tutor with different medical backgrounds and one ***Gastroenterologist*** (a professional with speciality in digestive system and its disorders).

Five actor patients took part in this experiment including: the research investigator's wife, and four colleagues. Volunteers ranged in age from 24 to 31 years old. The term actor patient refers to a normal human in average medical condition who has no known disease or abnormality at the time. Since this research intends to propose a reliable model for abdominal palpation examination, actor patients were selected with respect to anatomical variations and genders.

Body Mass Index (BMI) was used primarily to find potential participants for the three groups: Small, Medium, and Large (underweight, healthy weight, and overweight). It was difficult to find a female participant in the large category since it was neither ethical to ask a volunteer to take part because she is overweight nor possible in the short period of time prior to the experiment. Other medical indexes such as Body Adiposity Index (BAI) and Waist to Hip Ratio (WHR) were also employed to calculate excess abdominal fat concentration. Table 6.1 shows three commonly used indexes to assess healthiness for participants which were employed during the experiment.

The National Health System (NHS) web portal (National Health System (NHS) Choices, 2015a) the above metrics (BMI, BAI and WHR) could provide rough estimates of the participants' body type. The *Healthy Weight* region in BMI ranges between 18.5 to 25. Body Adiposity Index (BAI) was also used to determines percentage of the body fat from size of hip circumference and height (ShapeSense, 2015). The healthy region for this indicator is defined between 21% to 33% for a female and 8% to 21% for a male (age 20 - 39). Finally, Waist to Hip Ratio (WHR) is also used by some doctors (National Health System (NHS) Choices, 2015b) to

Table 6.1: Computed health metrics for the actor patients

| Gender | Size | BMI | BAI | WHR |
|---|---|---|---|---|
| Male | Small | 20.3 | 16.9% | 0.91 |
| | Medium | 23.6 | 21.0% | 0.97 |
| | Large | 29.5 | 25.6% | 1.01 |
| Female | Small | 16.2 | 22.7% | 0.85 |
| | Medium | 18.6 | 23.3% | 0.86 |

determine if a person carrying too much weight around his abdomen. A ratio above 0.85 for females and 1.0 for males indicates the risk of abdominal obesity in future.

The final decision for assigning the participants in three anatomical categories based on their abdominal obesity were made by the medical tutors. Since the participants took part voluntarily in this experiment, selection of male in small category and female in large category were limited to availability of the research investigators colleagues.

## 6.4 Procedures

Four different sessions were scheduled according to the tutors and participants availability. The tutors were formally invited to take part in this experiment by email with enclosed ethics documentation. The actor patients also received an invitation email with their specific version of the ethics documentation via the research investigator's group mailing list.

All participants were introduced to the tutor in an induction meeting prior to the data collection. Participants were asked to attend in sequential order. It was estimated that the tutors would take twenty minutes for each participant based on the assumed time of five minutes per task with two and a half minutes minute rest intervals between tests. Also, five minutes preparation time was permitted between participants. In the preparation intervals tutors had five minutes to put on a polyvinyl glove, the ParsGlove, and to clean the ParsGlove surface with sanitiser gel. Meanwhile, the research investigator was responsible for preparing the interface and checking the captured data. Tutors were asked to perform the target palpation tasks (superficial, deep and liver) twice to guarantee sampling reliability.

The tutor and actor patient were surrounded by a curtain during examination and the software application was focused only on the actor patient's abdomen (area between participant's ribs and hip). During palpation tutors were positioned in the right hand side of the patient using their right hand to palpate. Target tasks shared a common entrance point: from the right hand side of the patient's abdomen but the liver palpation had a different movement pattern and hand formation. Palpation was started with a brief introduction from tutors and a short description of the palpation routine to the actor patient before each task. Data collection was initiated and terminated by the tutor's verbal signal for each task.

The male participant in the medium body category was not able to take part in the second tutor's data collection session. Also, as mentioned before in chapter 6 no data has been recorded for the female in large body category in this phase.

## 6.5 Results and Findings

The medical tutors' palpation data were analysed by the *Examogram* application to compute the following attributes for all pressure sensors: frequency of presses, highest peak force per each press, and duration of each press. The raw pressure values were in an arbitrary unit format based on 10 bits of data ($0 - 1023$). The applied force upper-bound threshold (600 arb. unit) was chosen from the tutors' data in the deep palpation examination task and this region was divided into four quartets to represent very light ($Q_1$), light($Q_2$), medium ($Q_3$) and hard ($Q_4$) presses. Figure 6.1 shows the medical tutors' raw data on a histogram in superficial and deep palpation tasks.

Moreover, force distributions were computed and visualised on a palpating hand image. Each sensor's contribution ($C_{sensor}$) in the palpation examination process is computed as a function of the total captured press counts from that sensor ($PC_{sensor}$) and the total captured press counts ($PC_{total}$) from all twelve sensors (see Eq. 6.1).

$$C_{sensor} = \frac{PC_{sensor}}{PC_{total}} \times 100 \tag{6.1}$$

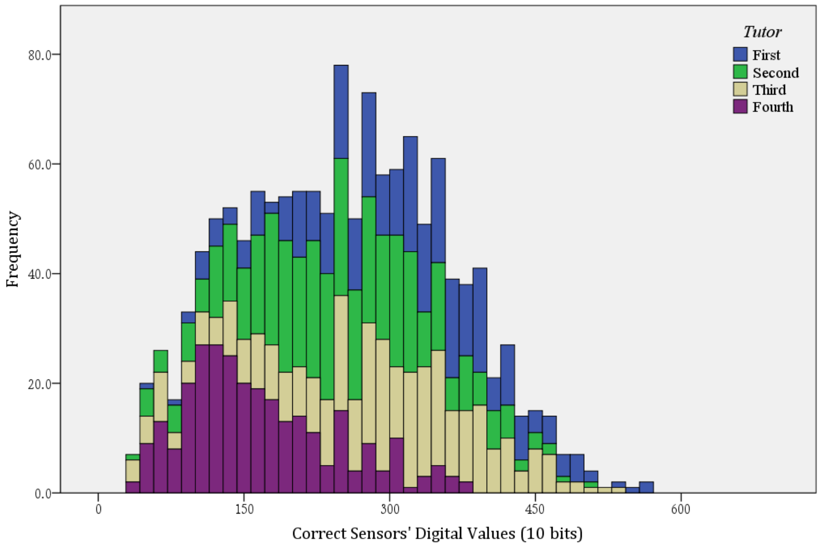
### 6.5.1 Assessment Framework

Participants' raw data were imported into *Examogram* and electronic reports were generated to highlight force properties such as magnitude and distribution across the hand surface and around its edge. Reports were sent to inform participants about their overall performance. Figure 6.2 shows an electronic report for a superficial palpation.

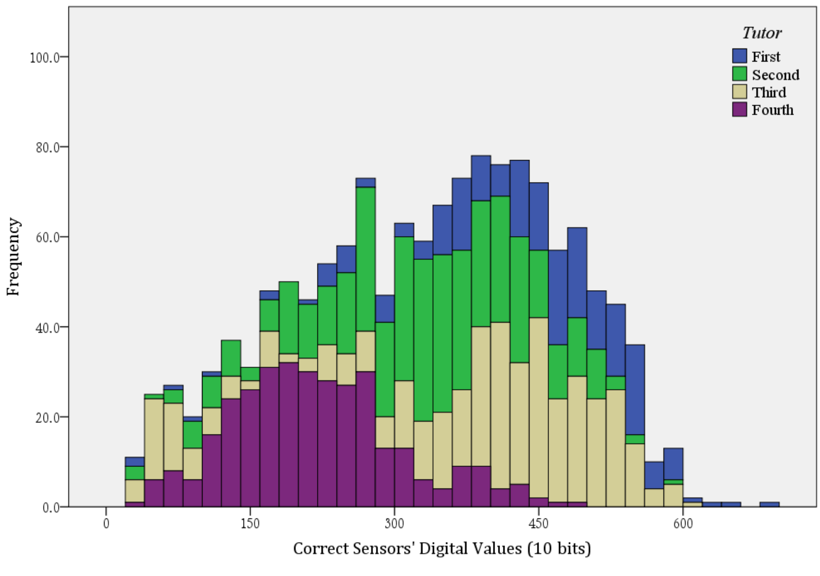
All reports were anonymised and presented to a lead medical tutor in a follow up meeting to interpret and design an assessment framework for computer-based assessment. Three criteria were defined by the medical tutors to mark students' performance. Each criteria has ten points, hence the maximum score is thirty.

Press frequencies and maximum force applied per press are calculated per sensor on the first version of the electronic reports. This quantity is used in the second set of reports to score students' performance in each criterion both in computer-based and human-based assessment methods.

***Wrong Use of Hand:*** Thenar and Hypothenar eminences on the palm are not supposed to be used on the patient's abdominal surface during the palpation examination process. It was suggested by the medical tutor to avoid leaning on the patient's abdomen during palpation since in real-world practice it may lead to patient's discomfort or further damages especially when they experience pain. Hence, hereafter we call the sensors that detect these actions, non-permitted or error sensors ($E_i$). This criterion should be met in all three tasks.




(a) Superficial Palpation - 65.6% of presses are in $Q_1$ $(0-150)$ and $Q_2$ $(150-300)$




(b) Deep Palpation - 60.1% of presses are in $Q_3$ $(300-450)$ and $Q_4$ (above 450)

Figure 6.1: Tutors' peak force distributions in four regions - superficial and deep palpation

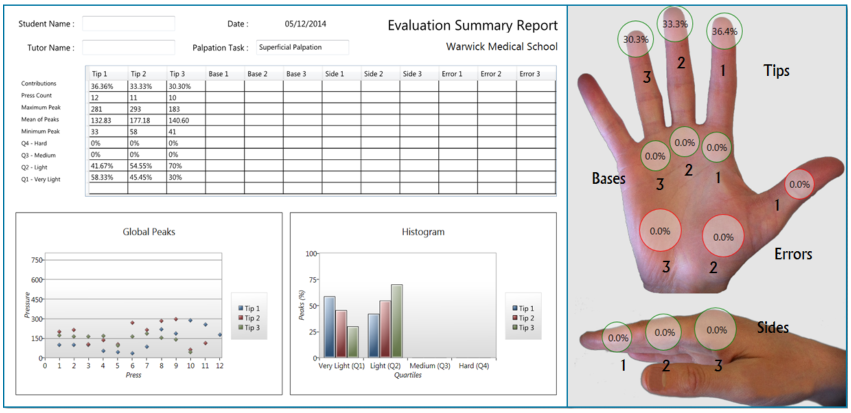



Figure 6.2: An example of the medical students' Preliminary reports to design the assessment criteria - superficial palpation

- Thenar eminence ($E_1 + E_2$) sensor's contribution (see Eq. 6.2):

$$C_{(E_1)} + C_{(E_2)} \leq 20\% \tag{6.2}$$

- Hypothenar eminence ($E_3$) sensors' contributions (see Eq. 6.3):

$$C_{(E_3)} \leq 10\% \tag{6.3}$$

***Correct Use of Hand:*** A good use of the hand refers to an equal balance between applied forces on the three fingertip sensors ($T_1, T_2, T_3$) due to the hand's posture in superficial and deep abdominal palpation. However, in palpation of the liver edge, it is important to employ only five sensors out of the nine permitted ones. These sensors are located on the radial border of the index finger (three side sensors), the index finger-tip and the index finger-base ($S_1, S_2, S_3, T_1, B_1$).

1. Superficial and Deep palpation: the variation ($\delta_{(T_i)}$) of each fingertip sensor's contribution ($C_{(Ti)}$) from the fingertip sensors' mean ($\mu$) are computed ($\delta_{(T_i)} = C_{(Ti)} - \mu$). Ten points were given when the differences are within and acceptable threshold (see Eq. 6.4).

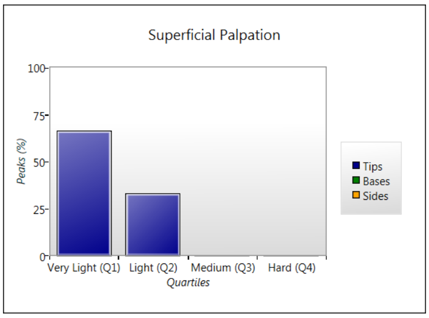
$$\delta_{(T_i)} \pm 20\% \tag{6.4}$$

2. Palpation of liver edge: Ten points were awarded if over half of the sensors' contribution in the examination process are focused on the radial border, finger-tip and finger-base of the index finger (see Eq. 6.5).

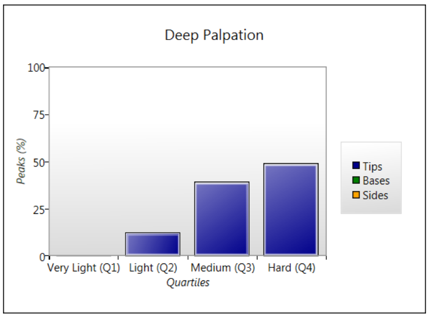
$$C_{(S_1)} + C_{(S_2)} + C_{(S_3)} + C_{(T_1)} + C_{(B_1)} \geq 50\% \tag{6.5}$$

***Force Magnitude Transition:*** Four different force magnitudes were defined based on the tutor's best-practice model: very light, light, medium, and hard press.

In superficial palpation the main objective is to perform a gentle examination, covering all regions on the patient's abdomen. While performing deep palpation the medical students must apply harder presses in order to locate organs or to identify abnormalities. Therefore, in superficial palpation examination the maximum peak of each press must be in the very light or light quartets whereas in deep palpation examination they need to be in medium to hard quartets. Figure 6.3 shows an excellent example of controlling this transition between superficial and deep palpation by a medical student in the visually-trained group.




(a) Very light to light presses




(b) Medium to hard presses

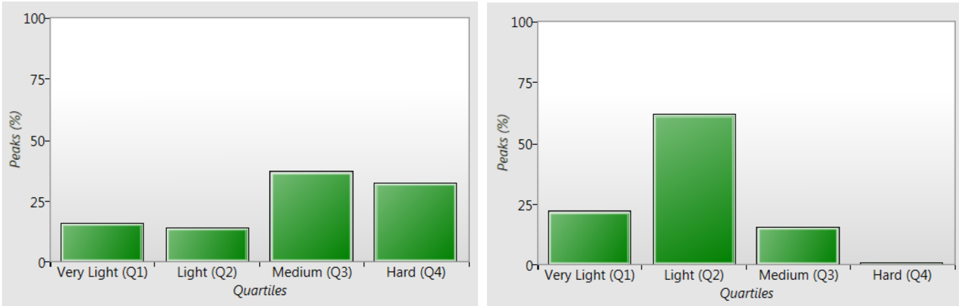
Figure 6.3: Applied force differentials

## 6.6 Findings, Discussion and Future Work

The analysis results were used by the tutors in the research and development stage to design a framework for further palpation performance assessments in section 6.5.1. Although, variations caused by the tutors and techniques are not investigated in this research, interesting patterns were identified in the medical tutors' dataset that could potentially present an opportunity to enhance the robustness of the research outcomes. These variations are discussed in following sections.

### 6.6.1 Variations across Medical Professions

Since the variation between tutors and their techniques is a well-known challenge in the medical domain, the best practice model is based on averaging the tutors' overall performance to cope with this problem. However, variation between medical professions is defined by medical tutors and it could have an affect on their force application magnitude. According to the medical tutors there are three definitions for medical professionals: ***novice, journeyman, and master***. Students are considered as novices and with the help of medical tutors who are in the journeyman category, they will learn how to perform palpation skills. However, the last group are domain specialists (Gastroenterologist) who are considered as masters in abdominal palpation examination skills. Hence, a light to moderate press could give them enough information about the potential abnormality in a deep palpation examination (see fourth tutor's performance in deep palpation figure 6.1) but examination with the same force magnitude might be insufficient for a medical student (novice) to diagnose the condition correctly. Figure 6.4 illustrates a comparison between journeyman (third tutor) and master (fourth tutor) performances in our study.




(a) Current Tutor (journeyman) (b) Gastroenterologist (master)

Figure 6.4: Variation in tutors' specialities effect on application of force in deep abdominal palpation. Figure (a) highlights harder presses compared to figure (b).

### 6.6.2 Variations across Genders and Body Types

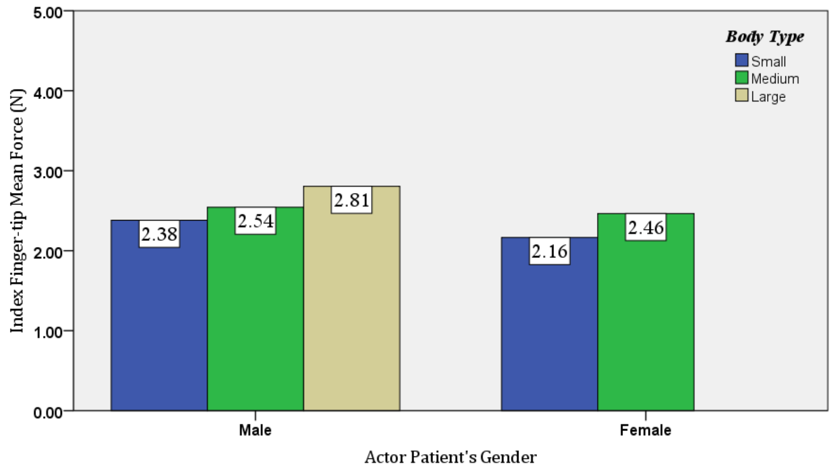
Slightly higher forces were recorded on finger-tip sensors ($T_1, T_2, T_3$) for male actor patients during superficial and deep palpation examinations by medical tutors. This could be explained by the anatomical variations between male and female. The required force to detect organs and abnormalities has a positive correlation with abdominal obesity because of a thicker layer of fat around the abdomen. This means harder presses are essential on a larger anatomy in both superficial and deep palpation tasks. Figure 6.5 shows the index finger-tip sensor's mean force (in Newtons) in superficial and deep palpation examinations for different body types across genders.

Also, the tutors' performance in deep palpation examination on males with large body for the finger-tip sensors ($T_1, T_2, T_3$) were plotted to illustrate the variations between palpation techniques among tutors in current practice. According to the generated force-time plots which are presented in figure 6.6, the first tutor had harder presses for longer durations compared to all other experts with fewer regions to examine (six press-release actions). The second tutor had the longest examination (twenty one press-release actions) with moderately equal amount of force in each. The press-release durations and subsequently the total examination time were arguably decreased in the last two performances. Finally, the last tutor (the Gastroenterologist) had the lowest force readings among others close to his superficial levels. In a follow up meeting with the lead tutor in criterion design stage this was explained as being based on the last tutor being a master in abdominal palpation examinations; it is possible for him to detect abnormalities in internal organs with a very shallow press but it is not recommended in training on the deep palpation examination since novices are not as sensitive as him due to the lack of cognitive understanding of abnormalities.

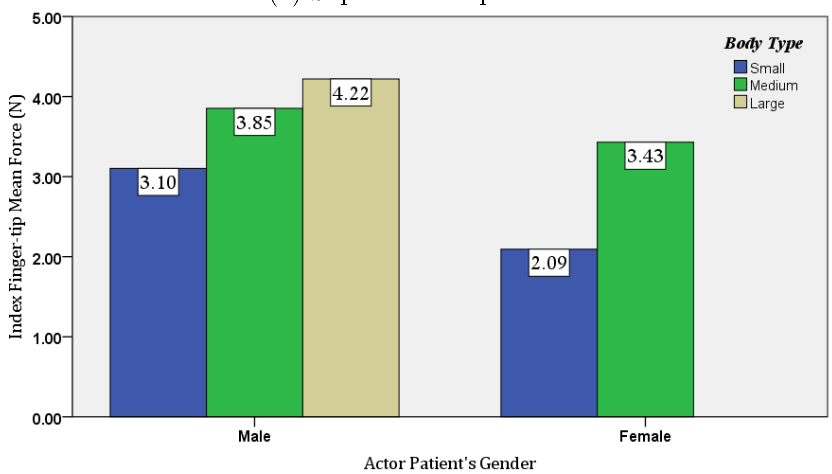
Research on how to resolve the variations between professions is out of the current focus of this work but it is a crucial domain to be investigated in the future to develop a highly accurate palpation model as a generic guideline with help of augmented feedback in learning motor skills. The outcomes of this phase of the study were used for calibration, the evaluation experiment and the game-based approach. Three mean force levels were identified for the index finger-tip sensor as follows: superficial palpation ($M = 2.45$ N), deep palpation ($M = 3.24$ N), and lowest maximum force for deep palpation as the highest safe threshold for a small-female ($M = 5.19$ N). Finally, the rounded results ($F_1 = 2N, F_2 = 3N, F_3 = 5N$) were used as a legend later in the game-based training experiment.

## 6.7 Summary

Moreover, it is very interesting to observe their superb control over force application in each press-release action even though they were blindfolded to any sort of augmented feedback on applied forces.




(a) Superficial Palpation




(b) Deep Palpation

Figure 6.5: Finger-tip sensor's ($T_1$) mean forces for different anatomies across genders in superficial and deep palpation tasks

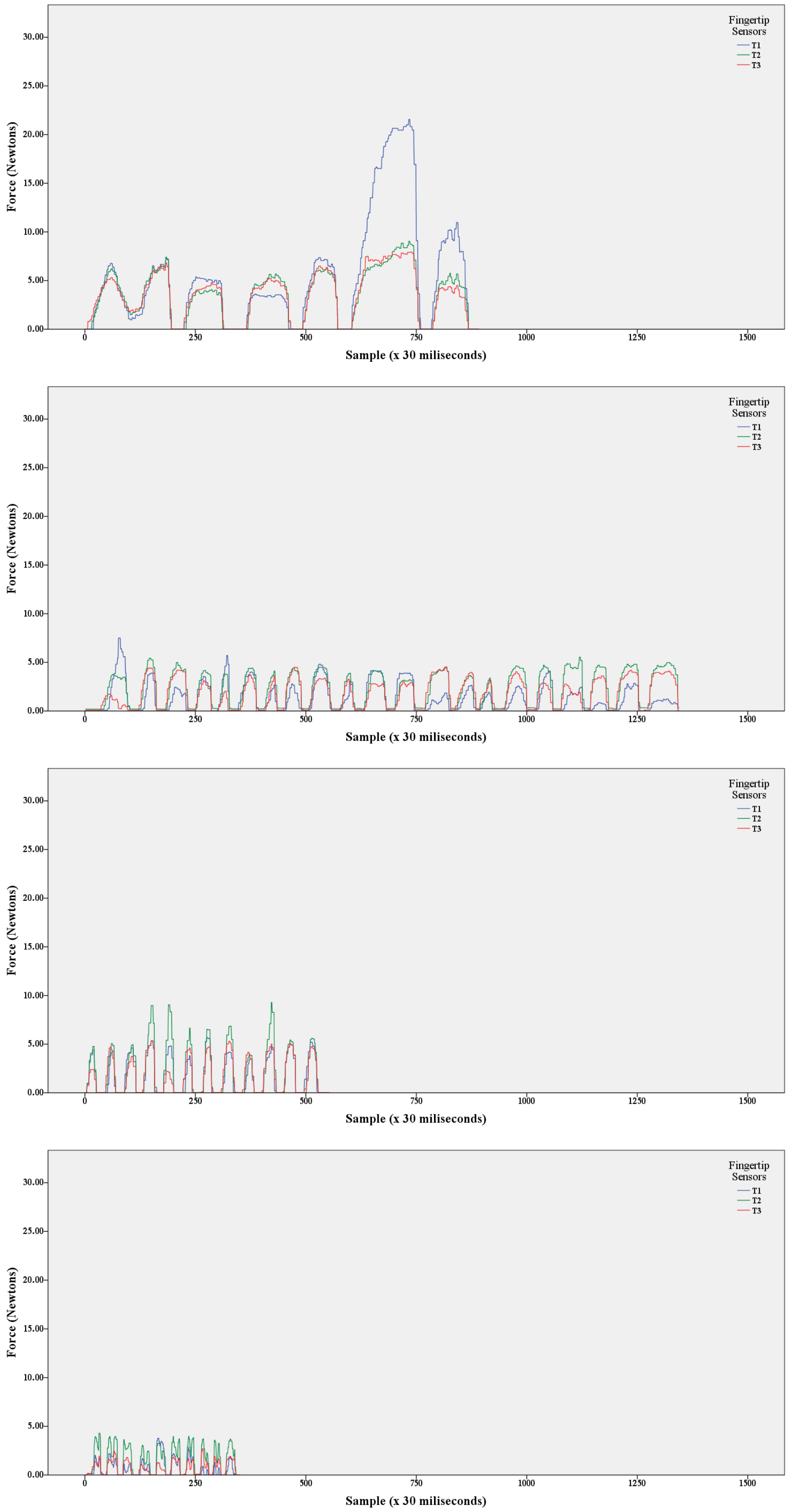



Figure 6.6: Variation in applied forces on large male anatomy

# Chapter 7

# Evaluation Experiment

## 7.1 Method

As the final stage of this research methodology, it was crucial to evaluate the impact of the proposed training and assessment technique in a real-world practice. Thus, a pilot study was planned in the focus group sessions to employ this technique in a formal training session.

### 7.1.1 Design

A between subject design was chosen for this experiment. Also, a systematic random sampling method (Schutt, 2011) was used to assign participants to one of the following three groups: A ***Control*** group ($n = 8$) to perform palpation examination in conventional fashion, a ***Semi-visually Trained*** group ($n = 8$) in which augmented feedback was delivered only in training phase, and finally a ***Visually Trained*** group ($n = 7$) where augmented feedback was provided in both training and actual test phases. One benefit of randomisation was to ensure there were no advantage between groups.

The motivation of this experiment was to answer the research question by exploring the effect of additional sensory information (e.g. visual feedback on applied forces) via different learning styles on cognitive and motor-control abilities to highlight any potential improvements in learning and performance. This effect was evaluated by comparing the students' competency in abdominal palpation examination with the best practice model which is proposed in the previous chapter as a trusted reference model.

Our main hypothesis in this experiment ($H_1$) was that additional sensory feedback on applied forces by the medical students' hands will improve their competency in abdominal palpation examination. The null hypothesis ($H_0$) was set to no difference between groups in their overall performance scores.

The independent variable in this experiment is the learning style which varies between groups. The effect of learning styles on the medical students' competency in abdominal palpation examination is defined as the dependent variable in this experiment. Table 7.1 shows an overview of the experimental design and different methods of training and test phases between groups.

Table 7.1: Evaluation Study - Experimental Design

| | **Control** | **Semi-visually Trained** | **Visually Trained** |
|---|---|---|---|
| **Familiarisation** | Visual Feedback | Visual Feedback | Visual Feedback |
| **Training** | No Feedback | Visual Feedback | Visual Feedback |
| **Test** | No Feedback | No Feedback | Visual Feedback |

In addition, to minimise the influence of additional factors on students' abdominal palpation competency the following control decisions were made prior to the the experiment.

- ***Same Quantification Tool:*** ParsMoCap palpation interface was used throughout the quantification process. Also, all groups had equal chance prior to their data capturing sessions to acquaint themselves with wearable interface in familiarisation phase.

- ***Same Training Session:*** it was essential to capture data from all participants in the same training session to ensure they have had equal amount of training prior to the experiment in their formal practice session.

- ***Same Palpation Tasks:*** the medical students in all groups were asked to perform the three target palpation tasks in similar orders with four regions of abdomen technique.

- ***Same Level of Knowledge and Experience:*** homogeneity in target population was a key to recruit participants. Thus, first year medical students were targeted to ensure participants are in the same level of knowledge and experience in clinical skills. All participants were debriefed by the same tutor prior to the experiment.

- ***Same Actor Patient:*** as noted already in the previous chapter the actor patient's anatomical variations will seriously affect on the force requirements for a best practice model. Thus, same actor patient is involved in all palpation sessions.

- ***Similar Distribution of Genders:*** participants were chosen from two genders by research investigator's request at the end of each data capturing session. Thus, equal number of male and female participants were assigned to the groups to control the influence of this factor on outcomes.

### 7.1.2 Materials

The primary materials used correspond to the technologies discussed in chapter 5. Despite the fact that all three previously defined palpation metrics for reconstruction of a hands-on practice (*Position, Orientation, Pressure*) were collected form ParsMoCap palpation interface but this study has focused only on force related information in this experiment.

The ParsDAQ data acquisition user interface was used on a laptop to capture raw digital outputs form the twelve force sensors from ParsGlove wearable sensory input. Force-related metrics were illustrated on a secondary panel in ParsMoCap application for technology-aided groups since the main application panel has additional information about orientation and positions which may distract the participants from the experiment's focus. This panel was dragged and dropped into the extended monitor by the research investigator to provide visual feedback for technology-aided groups. The laptop monitor was positioned in front of the research investigator to let him monitor the experiment's progress on ParsMoCap primary application panel and it was obscured from participants during the whole experiment.

Examogram data analysis user interface was used to run preliminary queries on the captured data to present these information on instant electronic reports for further evaluation by the medical tutors.

A TFT displays were used in extended mode to provide visual feedback for participants. This monitor was positioned in front of each participant to visualising the glove sensors' force magnitude and its location on hand.

A Kinect® v1.0 was attached to an off-the-shelf mounting rack to provide 90 degrees base rotation in order to capture patient's abdomen from the top view. Kinect® v1.0 mounting rack was fixed on a T shape adjustable frame which is fabricated from lightweight aluminium beams. The structure is designed by the research investigator and it was manufactured in-house with the help of workshop staff in Warwick Manufacturing Group (WMG) department to resolve health and safety concerns. Two flexible lamps were attached to the frame to provide extra lighting if it was necessary. Figure 7.1 shows the experiment settings in UHCW.

Figure 7.1: Evaluation Study - Environmental Settings (University Hospital Coventry and Warwickshire)

A proper hospital bed with ability to electronically adjust the height was provided in the training room. The distance between actor patient's bed surface to Kinect® v1.0 lens was adjusted to its previous setup for tutors' session in the research investigator's laboratory.

To meet hygiene and safety requirements in this study, an ultra thin powder coated polyvinyl glove is provided to each participant before asking them to wear ParsGlove to avoid skin irritations and electrostatic shocks. Moreover, a medically approved sanitising hand gel is used on ParsGlove surface before each examination similar to the real-world practice to avoid skin irritations or infections caused by medical students' palpation on actor patient's abdomen.

### 7.1.3 Participants

Twenty three participants took part in this experiment in three groups with twelve females and two left-handed subjects. Except the last group ($n = 7$) each group had eight participants. They all had normal or corrected to normal vision. All participants were chosen from first year medical students in Warwick Medical School (WMS) to minimise the influence of having prior knowledge and experience on students' competency results. A Participant Information Leaflet (PIL) and related ethics documentation were attached to the students' invitation email before the experiment day to debrief the participants about details prior to the experiment. Involvement in this experiment was entirely on voluntarily basis with the right to withdraw at any point.

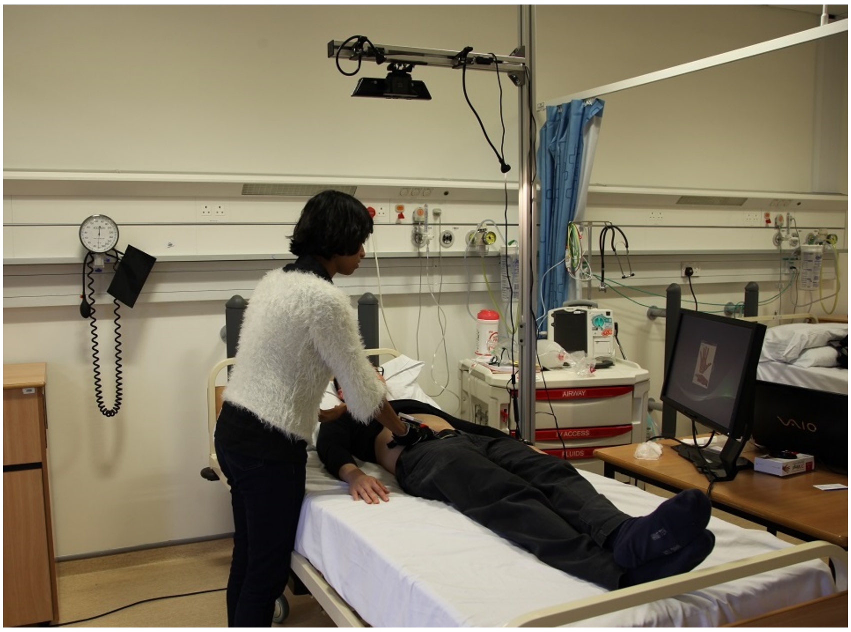
The research investigator's colleague took part in this experiment as the actor patient. Since he is a graduated medic, his report was extremely valuable both on his experience as the patient and on the palpation process as a professional.

### 7.1.4 Procedures

Prior to each session a brief description of the experiment was provided in four slides. Medical tutors were asked to provide one student by the research investigator's request. In each trial only three people were in the experiment room: the research investigator, the actor patient, and the medical student. Each participant was greeted by the research investigator and the actor patient and has been debriefed by the research investigator about the experiment procedure. A signed consent form was taken from each participant by the research investigator and an email was voluntarily provided for electronic reports.

A training phase and an actual test phase were planned for each target abdominal palpation examination task. Different learning styles were employed in each phase according to the participant's group. In addition, they were asked to conduct the examination session for each task similar to its real-world practice. Figure 7.2 shows the experiment room and different learning styles (*Conventional and Technology-aided*).


(a) Conventional Learning Method




(b) Technology-aided Learning Method

Figure 7.2: Experiment room and two different learning methods to teach abdominal palpation examination.

Participants began with introducing themselves to the actor patient followed by a brief explanation on the examination process. During the session the patient's facial expressions were monitored by the participant for any sign of discomfort. The data collection process was initiated and terminated for each abdominal palpation task by the students' verbal signal. Finally, raw data samples were labelled and stored on the research investigator's laptop.

## 7.2 Competency Assessment

Students' competence in performing target abdominal palpation examination tasks is defined as their performance. Medical tutors currently assess students' performance by skills observation and question/answer techniques as part of conventional assessment method. An Objective Structured Clinical Examination (OSCE) checklist which is specifically designed for this purpose is presented in appendix A.3. An assessment criteria was designed and proposed with the help of medical tutor in previous stage. In this stage, potential role of instantly generated computer-based reports On students' competency assessment process was explored.

### 7.2.1 Computer-based Assessment Method

A second version of the report was generated using a computer-based assessment approach to visualise the analysis results for different criteria in the assessment framework. Except the last criteria in which only two palpation tasks were assessed (Superficial and Deep) the overall score is computed by averaging scores for all three tasks. Three randomly selected competency report that was generated in computer-based assessment phase are presented in figure 7.3 for control, figure 7.4 for semi-visually trained, and figure 7.5 for visually trained groups.

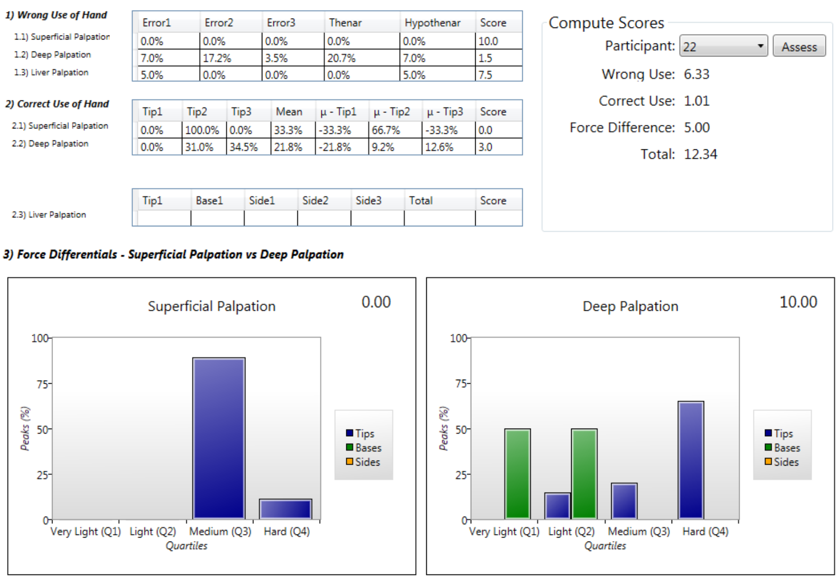



Figure 7.3: Computer-based assessment report - participant 22 from the control group

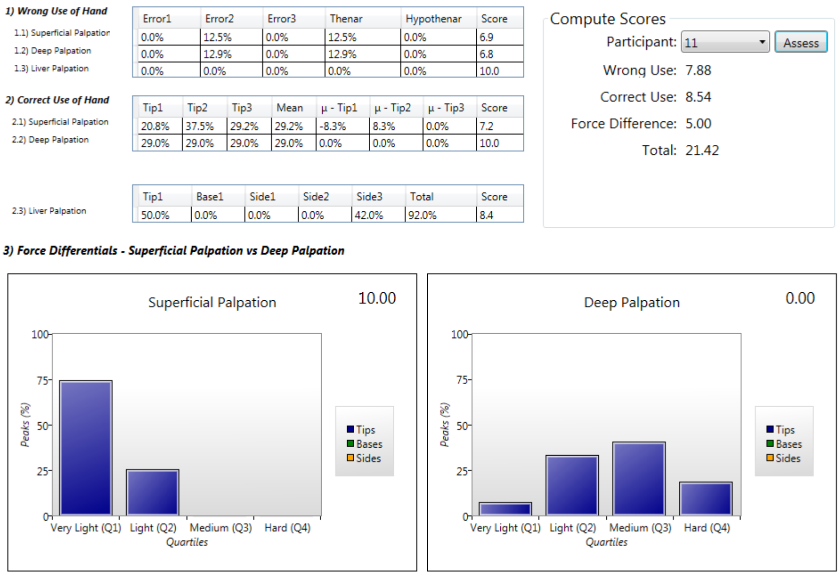



Figure 7.4: Computer-based assessment report - participant 11 from the semi-visually trained group

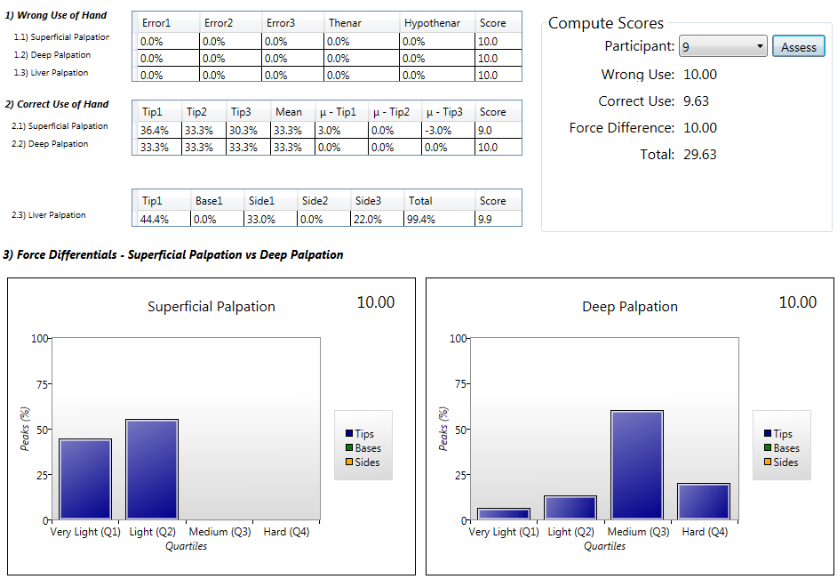



Figure 7.5: Computer-based assessment report - Participant 9 from the visually trained group

In this method ten points in each category was awarded if the target assessment criteria was met otherwise the absolute error was computed to reduce the final score.

### 7.2.2 Human-based Assessment Method

The computer-based assessment second reports were given to two medical tutors for a human-based assessment session. Tutors were not aware of students' names or their group and computer generated scores were also removed to avoid any bias. All reports were individually assessed by two medical tutors and a final score out of thirty was given to each participant. The final score then converted to a representative categorical value (*Fail, Borderline, Pass, Good, Excellent*) according to the Objective Structured Clinical Examination (OSCE) global rating template (MRCS, 2015). Finally, the two medical tutors made a combined decision for each participant by reviewing scores together. A one-to-one feedback form is provided to those participants who were failed or their score was on borderline to highlight their strengths and weaknesses. Table 7.2 shows the final outcomes for three groups.

Table 7.2: Human-based assessment rates

| | **Fail** | **Borderline** | **Pass** | **Good** | **Excellent** |
|---|---|---|---|---|---|
| **Group A (n=8)** | 6 | 1 | 1 | 0 | 0 |
| **Group B (n=8)** | 2 | 2 | 4 | 0 | 0 |
| **Group C (n=7)** | 2 | 0 | 2 | 2 | 1 |

Although, human-based scores were generated according to the assessment criteria but the important role of tutors in assessment process is clearly evident in the results. For instance our last participant in group C has achieved a remarkable score of 23.15 in computer-based assessment method and 19.5 in human-based assessment method out of thirty but since the correct use of hand in palpation of liver edge indicates no reading from target sensors at all a final decision of *Fail* is given in a combined decision by tutors.

### 7.2.3 Results

A non-parametric Kruskal–Wallis test is used on categorical results (OSCE ratings) as an equivalent counterpart for one-way ANOVA to ensure the results are not affected by the small size of samples. Also, equal variances were reported among groups, $F(2, 20) = 2.240$, by a Levene's test on assessment ranks. Students' abdominal palpation performance were reported to be significantly affected by presence of visual feedback on applied forces $H(2) = 6.033$, $p < .05$. Thus, null hypothesis ($H_0$) is rejected.

A *Post hoc* pairwise comparison test using the Bonferroni correction is also revealed that the mean score for training and test with the technology-aided learning method (M = 2.00, SD = 1.53) significantly differed from a blindfolded performance

(M = .38, SD = .74). However, providing technology-aided learning method only in training session (M = 1.00, SD = .76) did not show significant difference from the other two conditions.

Also, positive trend in students' performance improvement is reported by Jonckheere–Terpstra's test results when visual feedback on applied forces is used in palpation sessions. The median rank increased in groups, $J = 132$, $z = 2.62$, $r = 0.55$. Figure 7.6 shows this trend.

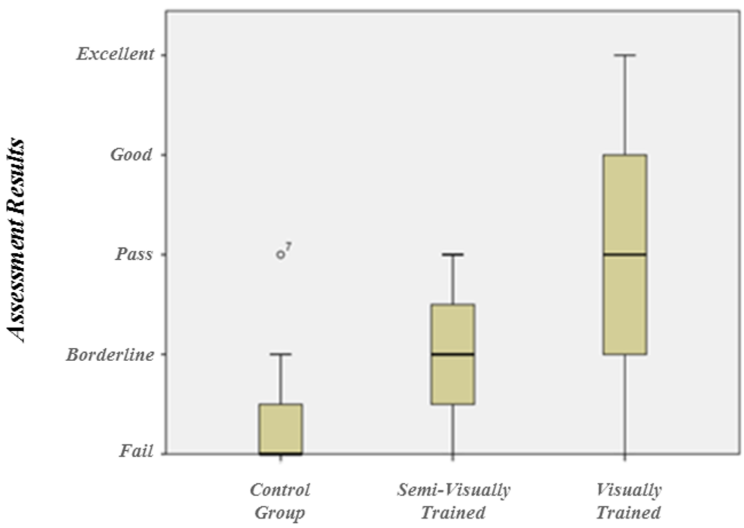



Figure 7.6: Gradual improvement in the medical students' palpation performance (between subjects)

Significant correlation is reported between computer-generated scores and human-generated scores, $r = .62$, $p$ (one-tailed) $< .05$. This indicates the potential of the computer-based assessment technique to assist current assessment process in medical education.

A post hoc power analysis is used to compute the statistical power $(1 - \beta)$ of this method as a function of type I error ($\alpha = .05$), the obtained effect size ($f = .67$) in current study, and total number of participants ($N = 23$) in G$^*$ Power 3 application (Faul et al., 2007) in order to evaluate the likelihood of detecting true effect. Power calculation result shows one extra participant per group ($n = 9$) could improve the obtained power (.76) to the recommended level (.80) Cohen (1977).

## 7.3 Qualitative Survey on Usability of the Proposed Method

The medical students in semi-visually trained and visually trained groups who had a chance to employ the new technology-aided technique, were asked to comment on their experience in contrast to the conventional method of training. Thus, A feedback form was prepared for this experiment with two different types of qualitative data collection methods. In this section the medical student responses to the new learning method are presented.

### 7.3.1 Design

First section of the feedback form was adapted from System Usability Scale (SUS) concept with close-ended rating scales to let the students rate usability of the technology-aided method. Also, a series of open-ended questions were provided in the last part of the form. The usability feedback form were given to the participants in group B and C since they have had a chance to try the technology-aided method as a learning tool. Eleven forms out of fifteen were received from the students comprised of seven females with one left handed subject. A copy of this form is enclosed to the appendix A.4.

### 7.3.2 Close-ended Rating Scales

In first part of the form, students were asked to choose the corresponding number for the most relevant answer. A five point scale rating system is used with the following choices:

1. disagree strongly
2. disagree
3. neither agree nor disagree
4. agree
5. agree strongly

Table 7.3: Evaluation Study - Usability Rates

| **Questions** | **Score** |
|---|---|
| This tool has potential as a learning aid for investigation training | 4.46 |
| This tool has potential as a learning aid for superficial palpation training | 4.63 |
| This tool has potential as a learning aid for deep palpation training | 4.72 |
| This tool has potential as a learning aid for locating specific organs (i.e. liver) | 3.89 |
| This tool provide a close to real experience | 4.11 |
| This tool is comfortable and lightweight to be used as a learning aid | 4.54 |
| This tool has potential to contribute to patient safety | 4.35 |
| This tool has potential to contribute to patient dignity | 3.57 |
| This tool has potential to contribute to patient experience | 3.89 |
| This tool is very beneficial to enhance conventional learning methods | 4.64 |
| Left/Right handedness may effect on leaning these skills (Left Handed only) | 3.00 |

Z-score to percentile rank method is used to analyse the results in this part since this metric offers a reliable precision because of using mean and variability in the scores. In a five point rating scale 80% of the number of points is calculated ($5 \times 80\% = 4$) to form a reasonable benchmark. Mean score ($\mu$) is compared with this benchmark value by finding the difference ($\delta = \mu - 4$). finally a z-score is computed by dividing this difference to standard deviation of the ratings for each question ($z = \frac{\delta}{\sigma}$). z-score is converted to representative percentile rank by looking at the table for a one-tailed approach.

Vast majority (81%) of the participants in this survey (n=11) from the technology-aided groups who have returned their feedback forms, agreed that this method has a potential in leaning abdominal palpation examination skills. The potential usability of this method is also surveyed in a task-specific level in which majority of students agreed its potential ( (89%) for Superficial and (94%) for deep palpation). One good reason for a better score in deep palpation could be the necessity of a clear definition for a deep press to avoid any hesitation. However, a lower score of (46%) is achieved for locating organs in the third target abdominal palpation task (liver palpation) which could be explained by the wearable interface. Fifty eight percent of the students have described their experience as close to real. Moreover, the measurement interface in this learning method was described as very comfortable and very light-weight (85%). It was also stated as a potential tool to contribute to patient safety (70%) but less likely to contribute to patient dignity (35%) and to patient experience (45%). Finally, a very promising score (90%) were given to this method as a beneficial learning approach to enhance conventional abdominal palpation examination practice in current medical education. Since only one left-handed person was participated in this survey, it neither agreed nor disagreed that left/right handedness may affect learning these skills.

### 7.3.3 Open-ended Questions

The students gave answers to five open-ended questions in second part of the feedback form. Written answers to the questions were summarised in following categories:

**Learning Outcomes:** The answers to the first question highlight better understanding of force differentiation for each abdominal palpation task. One student explicitly discussed about potential hesitation in palpating hard and deep enough due to lack of a clear definition for deep palpation ‘Not to be afraid to palpate more deeply + risk discomfort for the patient’. In addition to that, better understanding of correct and effective use of the palpating hand per each abdominal palpation task were indicated among the answers.

**Strengths and Weaknesses:** properties such as enhancing the palpation accuracy, contribution to patient’s safety, instant feedback on applied forces, navigation based on tutor’s best practice, ease of use and high sensitivity to application of force by the palpating hand were discussed as key strengths of this method. Potential weaknesses were also identified among the answers.

## 7.4 Actor Patient’s Feedback

The research investigator’s colleague was invited to take part in this experiment to act as a patient. Since he is a graduated medic, his participation added more value to the observation process. The medical students were monitored for variation of techniques and their competence in conducting examination process. In this section brief review on actor patient’s experience is presented.

### 7.4.1 Examinee background

- Medical doctor, male, age 36 (during examination)
- No known medical conditions
- Soft and non-tender abdomen with no abnormal enlargement of organs
- Slim build body type with BMI of 24.5

### 7.4.2 Examinee comments on measurement interface

On examination (superficial, deep, and liver palpation), the sensation of the glove on the abdominal skin is stated as comfortable with no hard or sharp edges or excessive friction when used by a competent examiner. Also, the motion capturing part of interface (Kinect® v1.0 and aluminum frame) was described as non-intrusive with ability to comfortably lie flat beneath it.

### 7.4.3 Examinee feedback on examination sessions

Despite having just attended a second clinical examination skills tutorial, notable variation in the performance and a few competence issues were observed during participants' examinations. One or two participants were described as very confident on examination and a lot more skilled than the others. A few needed reminders on examination technique with two subject who applied a completely wrong technique in the palpation of liver edge. This may be due to a lack of confidence, enough practice, and/or previous related experience in palpation examination (WMS four years curriculum scheme). Otherwise examination routine was descried as gentle with the participants checking if the examinee was uncomfortable (i.e. good bedside manner).

***Superficial palpation:*** according to the actor patient's observations, participants were mostly competent and all abdominal regions were covered. Some seemed to examine four quadrants or nine segments systematically. Palpation proceeded from the right lower quadrant, right upper quadrant, left upper quadrant, left lower quadrant (clockwise), or the reverse. However, a few appeared to palpate locations seemingly randomly either adequately covering the entire abdomen or missing some areas. One participant had an interesting technique of rapidly wiggling the tips of the palpating fingers in a circular fashion akin to a massage.

It is worth noting that as the actor patient's abdomen was non-tender, participants may not have been prompted to begin the palpation in any particular area. Typically palpation begins away from the tender area and moves carefully towards the tender area.

***Deep palpation:*** participants were reported as mostly competent with all areas covered as above. Usually a repeat of the superficial palpation locations but with more pressure (albeit subjectively gently to the examinee). In retrospect, it was reported that participants palpated more deeply when visual feedback of pressure was provided via the glove and monitor. This may be confirmed by the data recordings. In addition, as the actor patient's abdomen was non-tender and he was tolerating deep palpation without complaints, the participants were probably encouraged to test the depth of deep palpation. The same participant who used the circular motion in superficial palpation was reported to use the same approach again but with this time with more pressure.

***Liver edge palpation:*** participants were addressed as mostly competent with the radial border of the index finger being depressed against the abdomen, beginning from the right iliac fossa upwards to the right costal margin, synchronised with instruction to inhale deeply. A correct variation in technique involved the tips of the fingers were reported during examination but this was in the minority and the former method was used instead. Two participants were noted to the use of the ulnar edge of the hand which is technically wrong.

## 7.5 Discussion and Future Work

However, availability of the particular type of participants (first year medical students) in this study and intervals to the next available teaching sessions were key limitations to this research due to its time constraints. Thus, additional evaluation studies are planned in future work.

Significant improvement in learning abdominal palpation examination skills is reported by results to highlight the impact of a technology-aided approach to enhance conventional teaching methods. Moreover, potential benefits of such a method were stated in obtained usability feedback in the qualitative evaluation. One student explicitly shows her motivation to use this technique as part of her education.

> 'Very good tool which I think has the potential to improve abdominal palpation skills a lot. Excellent idea. I hope it is used more widely in the future.' *female, group C*

Apart from the importance of precise control over applied forces during abdominal palpation, the palpating hand's posture and its movement patterns in different abdominal palpation tasks are key elements to be learnt by medical students. As part of this learning objective correct distribution of forces were investigated in this study but 3D reconstruction model of tutors' palpating hand is planned to be presented for motor movement. Moreover, further collaboration with medical professionals could improve the robustness of the so-called best practice model for target abdominal palpation tasks. A complimentary experiment is also conducted by the research investigator in next section to explore the efficacy of such a technique towards a game-based learning approach on non-medical students.

# Chapter 8

# Towards Game-based Training

Game-based training is widely used in serious applications particularly in rehabilitation studies to deliver augmented feedback in motor (re-)learning process. It is an assumption that the fun factor in a game-based training approach may enhances motor performance and learning processes more than abstract visualisation of augmented feedback in a simple force exertion task. Thus, a haptic-enabled serious game training technique was designed and developed based on the ground truth exploration findings to evaluate if this method offers superior performance compared with abstract visualisation which is proposed in chapter 7.

## 8.1 Introduction

The efficacy of serious games as a training approach has become widely accepted and as a consequence serious games are beginning to be used in a wide variety of domains. Immersion, pleasure and competition are key characteristics of games that enhance user engagement in training activities. Apart from research studies even commercial companies are now interested in taking part in the development and deployment of educational games Wortley (2013).

One of the main domains demonstrating the fruitfulness of serious games is healthcare Arnab et al. (2012). A number of reasons have lead to the success of serious games for healthcare. Ethical restrictions in medical training mean that certain procedures cannot be frequently tested and explored by practitioners. Similarly, a lack of available patients during training entails limited familiarity with the application of procedures across a varying number of ages, genders and body types. Furthermore, the demands for patients' growing thirst for health information has led to health professionals providing novel digital-based interventions.

Current challenges in medical education are particularly difficult when the possibilities of experiencing training in that activity are rare. Game-based solutions can provide an enhanced experience to the existing educational process for such cases Sliney and Murphy (2008); Susi et al. (2007). One of the most common medical processes which are carried out by most medical practitioners in a very large variety of conditions and for a diverse number of applications is palpation (Macleod et al., 2009; Patel and Morrissey, 2011). Palpation plays an important role in the initial examination of patients and is a crucial initial diagnosis Goodwin (1995) based significantly on haptic sensory feedback. While visual and acoustic digital healthcare practices are becoming more common due to the ubiquitous nature of video and audio displays and their use in both entertainment and real-world applications, the lack of readily available haptic devices has meant very little progress has been made in the areas of motion and pressure sensitivity control within the healthcare domains.

This experiment is part of a larger project aimed at training medical students to become more proficient at palpation as part of their training process. Training in palpation is of crucial importance as during their training medical students are restricted to the number of hours they can spend with their tutors gaining hands-on experience and are also restricted on the number of body types and participants that they can engage with Duvivier et al. (2012). A goal of automating the process and providing palpation-based simulators will enhance current practices by allowing the students to practice by themselves or with each other while being guided via a digital tutor. This experiment identifies and focuses on one aspect of an automated palpation framework; training of pressure sensitivity using the index finger, one of the crucial characteristics of palpation training, is provided via the use of a serious game in which the player controls an on-screen character via the use of an input device which is sensitive to pressure. Learning to apply the correct amount of pressure plays a significant role in providing the correct diagnosis and also in patient comfort; a too light touch may miss out on important physiological phenomena and a too heavy touch may cause significant patient discomfort further compounding potential diagnosis issues. While a number of novel input technologies beyond the traditional have recently begun to be applied to serious games (Gotsis, 2009; Scarle et al., 2011; Schonauer et al., 2011; Saini et al., 2012) no serious game, to the best of our knowledge, has targeted the correct application of pressure as its main goal. A study based on two groups composed of general public participants, one group that played the game and a control group demonstrates that there is reason to believe that such a serious game can help improve pressure sensitivity in individuals.

The following section presents background and related work. Descriptive information of the three technologies which are used in this study is discussed in Section 8.3. The experimental design and results are discussed in 8.4. Finally future potentials for extending this study and conclusions are presented in 8.5.

## 8.2 Background and Related Work

In general, applications of serious games in healthcare can be classified by their target audience Kamel Boulos (2011) as follows:

- Medical education
- Patient intervention
- Public involvement

Games dedicated to medical education are those that help medical professionals to improve their skills while performing certain tasks. Patient intervention are targeted at patients rather than the medical professionals. Such patient-oriented training games help enhance individuals' knowledge about their condition and to also help improve their engagement in their treatment process. Public involvement applications are directed at the general public and are focused on raising awareness of public health issues and providing motivation for potential behavioural change. A large number of healthcare-related serious games have been developed Arnab et al. (2012) and we provide a small set of examples in the following.

In terms of medical education and awareness Graafland et al. (2012) presented a survey on medical education and surgical skills across 25 publications which comprised 30 games. They explained that games developed for the purpose of such serious applications required the use of further validation before being deployed as there was a lack of robust evaluation for the surveyed games. Dunwell and Jarvis (2012) presented a serious game to help create awareness of healthcare-associated infections within wards. They provide feedback and findings on the deployment of the game across 13 hospital wards in the United Kingdom. The serious game we present in this experiment could also be considered as part of the medical education sub-category of serious games.

An example of a patient intervention game was the Re-Mission game for cancer patients. Positive behavioral changes were reported on paediatric patients who were diagnosed with cancer by playing this video game Kato et al. (2008). Another patient intervention example was provided by Carmeli et al. (2009). The authors presented a serious game for the improvement of motor, sensory and cognitive performance in rehabilitation of stroke patients (with upper limb impairments) to conduct everyday functional tasks efficiently. An interactive tool was used as an input device for the game to measure range of motion and finger and wrist speed. Results demonstrated an improvement in movements for users.

An example of increasing public involvement was presented by Kamel Boulos et al. (2007) environment to raise public awareness about sexual health. An online 3D virtual world such as Second Life (SL) with social networking capabilities has been surveyed to highlight positive impact on its audience. Brown et al. (2012) also presented a serious game dealing with sex education in which an intervention mapping approach was used in the development and the design of the game. Scarle et al. (2011) presented a serious game that had two main goals focusing on public involvement. Firstly, it was targeted at raising the awareness of poor eating habits at primary school children that has been becoming one of the main causes of the rising obesity epidemic and, secondly, through the application of motion controls that enabled the participant to reduce the amount of on-screen time in which the game player was physically inactive.

## 8.3 Serious Game and Input Device

This section presents the overall framework that has been used for this experiment. Three key technologies including a serious game were developed to improve pressure sensitivity learning. The input device is a glove developed in-house and can read pressure the amount of pressure applied accurately in Newtons. An application, DigiScale, was developed to help facilitate the input procedure via a user friendly interface.

### 8.3.1 Input Device

A wearable measurement interface, ParsGlove (see Chapter 5) has been developed under formal R&D discussions with with medical professionals. It is designed to capture the ergonomics of the human hand during dexterous interaction with the environment. It was essential in our main goals to use the full capabilities of the glove to capture applied pressures, orientations and location parameters although for this experiment the focus is only on the pressure input.

To provide more freedom the glove is equipped with Bluetooth connectivity and is composed of ultralight materials which help reduce weight and avoid fatigue when the glove is worn for long periods. Twelve force sensitive resistors are mounted in places which were defined by medical professionals. Sensors were also calibrated with a force gauge device to accurately map digital values to actual force.

### 8.3.2 Application

DigiScale is a Graphical User Interface (GUI) specifically developed for this experiment to deliver visual feedback for the force exerted by the tip of users' index fingers. DigiScale has two sections: an information panel providing visual information directly to the user and a toolkit panel for the research investigator (see Chapter 5).

The information panel is designed to provide visual feedback of applied forces by the user, the target force level in each task and a countdown timer. The toolkit panel is designed to provide connectivity options to pair ParsGlove with DigiScale, three buttons to set the target force levels in each task and finally an export button to persist recorded samples at the end of each session. The application has capabilities to read continuous data streams over the Bluetooth standard which permits communication with the glove. The application could be run on any normal PC without any specific hardware or software requirements. The only requirement for this application is a Bluetooth receiver.

### 8.3.3 Game

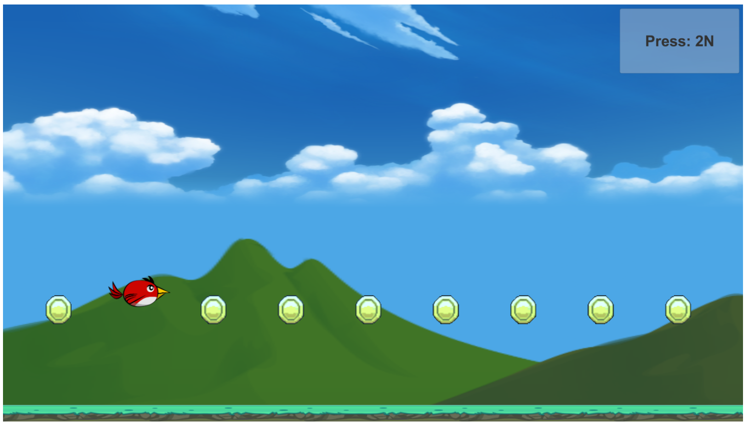
To provide game-based training to help improve performance, a 2D game was developed in the Unity 3D game engine. The game assets were adapted from free assets made available from the Unity store. The game was designed to interface with the ParsGlove playing the role of the game controller. Figure 8.1 illustrates a number of screenshots of the game in action. Figure 8.2 shows the game as it is being developed.

The goal of the game is to help users improve their pressure sensitivity by controlling a flying bird that soars higher based on the amount of pressure applied by the index finger of the user. The pressure applied is the only form of input.

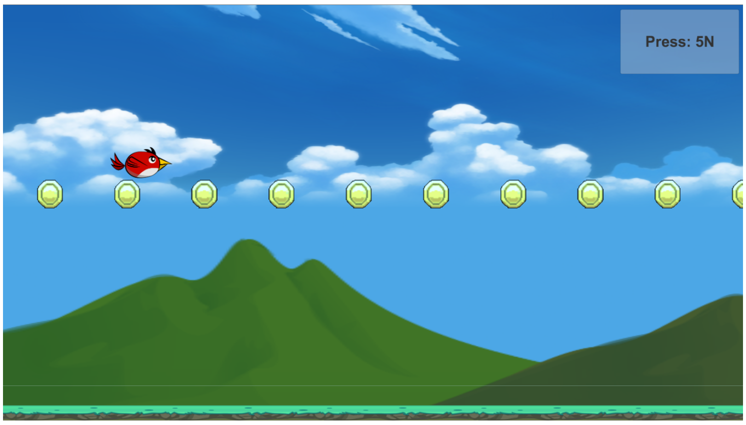
The gameplay is inspired by the infinite runner genre of games; although the play sessions have been limited in the interest of time. The objective of the game is for the bird to collect coins that appear randomly at three possible heights within the environment. The coins are randomly generated in different quantities from 5 to 15. Auditory feedback is also provided on successful coin collection.

The heights chosen correspond to the application of three levels of force. The three force levels are 2, 3 and 5 Newtons coinciding with very light to medium pressure. These forces were established through a pre-study with medical professionals in a process discussed further in Section 8.4.1. It is crucial for a medical student to control his hand in a dexterous manner to perform different abdominal palpation tasks. Hence, a very light amount of force such as 2 Newtons could be extremely challenging for a novice. Design of different tasks in game-based and application-based approaches were established on these guidelines.

A collision detection function is implemented to detect if the bird avatar hits a coin. The box collider used for coin to bird intersection has a buffer equivalent to $\pm 0.25$ Newtons along the height dimension. Players should collect more coins in order to achieve a better score at the finish line. A slight increase in the flying speed during the game as well as random generation of coins makes it more challenging for the player and has the goal of keeping the game interesting. An information panel is placed on the top right corner of the game screen to show which the next coin level is. This is demonstrated in Newtons for the user to form an association with the amount of pressure to be applied and the numeric value of the force. The information panel also provides a final score at the finish line. The screen height is normalised to represent 0 to 10 Newtons from bottom to top. Although, the player could reach higher levels of force by pressing harder, the limitation of 10 Newtons was chosen to meet safety regulations.




(a) Coins are spawned at 2 Newtons




(b) Coins are spawned at 5 Newtons


(c) Final score at finish line

Figure 8.1: A game-based training approach is proposed by this experiment to help users improve their pressure sensitivity by controlling a flying bird that soars higher based on the amount of pressure applied by the index finger of the user. The final figure demonstrates the score that is displayed at the end of a run. Each captured coin is worth £100.

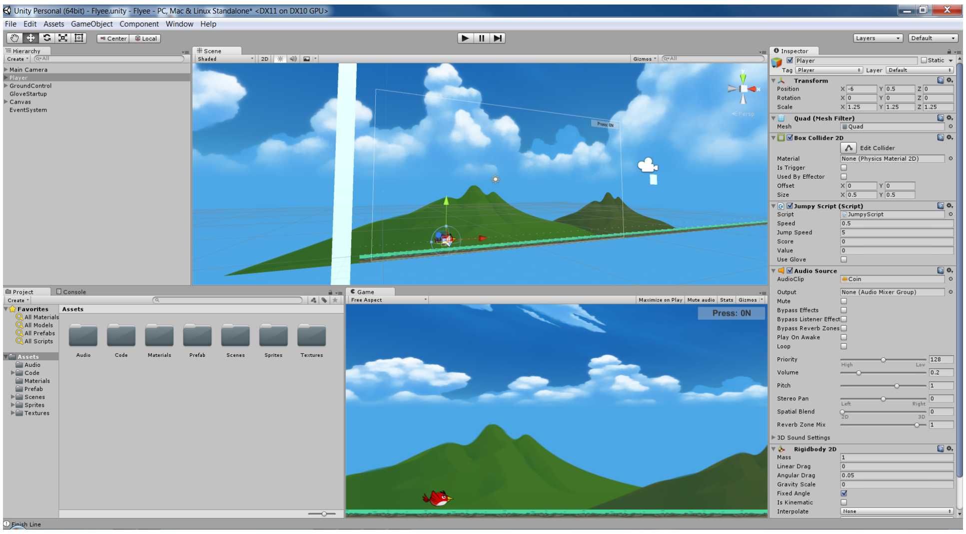


Figure 8.2: The game being developed within the Unity environment.

## 8.4 Experiment

In order to evaluate whether the game discussed in the previous section improves pressure sensitivity a participant-focused experiment was run. This experiment intends to explore if visual and auditory feedback of applied forces in the form of a game-based training approach could improve motor learning and control abilities on non-medical participants.

### 8.4.1 Method

A between participants design was chosen for the experiment. Participants were divided into two groups: Group A ($n = 15$) to be trained by the serious game and group B (n=15) a control group. All participants had been asked to apply force from their index finger tip while sat (in the stand up position kinesthetic help from shoulder may produce variation in the exertion of force) on a table as rigid surface. The exerted force values were sampled for each target force level for 10 seconds with 10 millisecond intervals resulting in 100 samples per each target force level. The three forces of $2, 3, 5$ Newtons that were the target goals where the coins were set in the game (as discussed earlier) were based on a pre-study in which medical tutors' pressure while palpating patients was captured. These studies involved the use of four medical professionals examining five different participants acting as patients composed of both genders and three body types. The data capture consisted of all the medical professionals completing three palpation tasks (liver edge, deep and superficial) for all the patients. All data was captured and analysed and the goals of $2, 3, 5$ Newtons were identified based on the mean force across the medical professionals in each task across the body types.

Table 8.1 shows an overview of the experimental design and training methods for each group. The familiarisation phase allowed the participants to acquaint themselves with the equipment and saw the actual value they were pressing on DigiScale. In the final test (no visual feedback) the participants could not see how much pressure they were applying on the display and had to rely only on their pressure sensitivity training. The difference between the target value and the recorded value (in Newtons) for the no visual test was used as the dependent variable. The null hypothesis H0 in this experiment was that there is no difference between the two groups in the accuracy of the exerted target force for the no visual feedback test session. The software used for the familiarisation DigiScale was significantly different from the environment found in the game to avoid any bias of familiarisation that may have led to the game playing group to have an unfair advantage during the testing phase.

Table 8.1: Game-based Training - Experimental Design

| | **Group A** | **Group B** |
|---|---|---|
| **Training** | Visual Feedback (GUI) | Visual Feedback (Game) |
| **Familiarisation** | Visual Feedback (GUI) | Visual Feedback (GUI) |
| **Test** | No Visual Feedback | No Visual Feedback |

### 8.4.2 Materials

The primary materials used correspond to the three technologies discussed in Section 8.3. DigiScale was used to convert the raw sensor value from the glove to force in Newtons and to provide visual feedback on the exerted force by the user for the Training and Familiarisation phases. Two TFT displays were used in duplicate mode to provide visual feedback for each participant and to let the research investigator monitor the experiment's progress. An ultra thin powder coated polyvinyl glove was used to meet hygiene requirements prior to provide the measurement glove to participants.

### 8.4.3 Participants

Thirty participants took part in this experiment in two groups of fifteen with seven females and one left handed participant. Participants all had normal or corrected to normal vision. Participants were members of staff or students contacted via internal university email. A Participant Information Leaflet and related ethics documentation were attached to the invitation email before the experiment day to debrief the participants about details prior to the experiment. Participation in this experiment was entirely voluntarily with the right to withdraw at any point.

### 8.4.4 Procedures

Each participant had been debriefed about the experimental steps by research investigators and via email prior to data collection. Each participant was asked to wear a powder coated ultra thin polyvinyl glove and confirm if the sensor on the index finger tip was positioned correctly.

Group A had 5 minutes training with DigiScale application. Group B had the same duration of training with the game in three rounds with one minute intervals between them. The reason for repeating the training for three attempts for the game group was to provide the player with variety within the game environment as aspects of the game are randomised.

In the familiarisation phase, which occurred soon after the training session, participants were asked to attempt to meet target force levels with the aid of a dedicated display that provided visual feedback via the DigiScale application. In the final no visual feedback test, the display was switched off and results collected for each participant. There was a one minute interval between training and tests to avoid human fatigue. For each target force the following objectives need to be achieved by each participant in each test.

- To reach the given target force level
- To maintain that target force level for 10 seconds.

### 8.4.5 Results

Results for each target force was obtained via the difference in target and recorded force for each observation. The mean exerted force ($\mu_i$) for each target force level ($f_i$) is calculated from collected samples for each participant. The absolute difference from the target force is calculated as:

$$\delta_i = |\mu_i - f_i|$$

The mean of the delta values for all three target force levels $f_i$ (2, 3 and 5 Newtons) were computed as a final result for each participant. A non-parametric Mann-Whitney test has been selected to analyse the results due to the non-parametric nature of the data.

The accuracy in the exerted target force for the no-visual test for participants in group B, who were trained using our game approach ($Mdn = 0.86$), differed significantly from the participants in group A, who trained using the application only approach ($Mdn = 1.56$), $U = 61$, $z = -2.137$, $p < .05$, $r = -0.36$ and thus H0 is rejected.

This result may highlight the potential role of game-based training on cognitive and control motor learning abilities. One possible reason for this achievement is an improvement in the understanding of the approximate force and sensitivity for the required pressure instilled while playing the game.

Another potential advantage of game-based training is the competition factor characteristic of games. It was observed during the experiment that participants in group B were keen to beat their previous best score in each round which may have led to better focus and concentration on the requested test.

### 8.4.6 Qualitative Feedback

In order to form an understanding of whether the game was considered an enjoyable experience, and whether it was well designed and engaging a number of questions were asked to the group that played the game. An electronic questionnaire was sent via email to each participant in the game group (n=15) to collect their reflective feedback on their experience when playing the game. A total of six questions were asked to rank key features of the game from 1 to 5 (e.g for first question the answer is made from Not at all, Slightly, Moderately, Very, Extremely "Enjoyable"). Fourteen out of fifteen participants replied and a mean scores for each question are reported in Table 8.2.

Table 8.2: Game-based - Usability Rates

| **Questions** | **Score** |
|---|---|
| Did you enjoy playing this game? | 3.85 |
| Did you engage with this game? | 3.85 |
| How would you rank this game in terms of design? | 3.85 |
| Did you feel any improvement in controlling your force level each time you have played this game? | 3.77 |
| Would you play the game again in future? | 3.46 |
| Would you recommend this game to a friend? | 3.54 |

Using rounded mean scores for a general evaluation the game can be deemed to be very enjoyable to play, very engaging, well designed, and with the ability to provide a perceived increase in motor ability. Participants also considered that they were likely to play the game again given the opportunity and would very much recommend it to a friend. On the whole, based on this feedback, the game design seems to have been for the most part successful.

## 8.5 Conclusions and Future Work

This experiment has presented a serious game that attempts to teach participants the correct application of pressure by controlling a virtual character on screen via a pressure sensitive input device that rewards players with accurate and controlled input. The results demonstrate that those players that played the game performed significantly better than a control group in a subsequent no-visual task within a very different environment from the game itself. Moreover, questionnaire responses indicate that the game is enjoyable and engaging. It is important to indicate that while this game has appeared to have been successful it is part of a larger framework that is required in order to make automated or assisted palpation training successful.

Future work will look into enhancing this experience by using all the input sensors on the glove, and the capability of the system to capture location and orientation data. This can be then used for the development of a serious simulator or serious game. Furthermore, palpation is not the only application that requires pressure sensitivity and modifications to the main game to adapt to the range of sensitivities of various applications can aid pressure sensitivity training in other fields eg. training for musical instruments.

# Chapter 9

# Conclusions and Future Works

This chapter concludes the thesis outlining contributions, limitations and future work.

## 9.1 Conclusions

Clinical palpation skills are a cheap yet very effective method of diagnosis. Thus, it is crucial for medical students to master these core skills and to ensure that they are retained throughout their career. This is very difficult to achieve without frequent and realistic rehearsals not only during academic training hours but also in the medical students' self-study time outside of the classroom. This work has presented a multimodal technology-aided technique to enhance conventional training and its assessment in medical education. An extensive literature review on mechanical, biological, psychological, and technological aspects of human motor learning particularly in practical hands-on interactions was followed by a comprehensive ergonomics study to understand the user and task requirements for accuracy and reliability of the method. Also, active involvement of medical experts (masters) and students (novices) in a UCD fashion was a key feature of this study to accurately design the research methodology and to evaluate its impact through real-world practice.

Palpation metrics were identified by medical tutors and a ground truth model was developed by averaging captured palpation data from a team of four medical tutors in order to minimise the variations in captured data. Moreover, an assessment criteria was defined with the help of the lead tutor based on the ground truth model. Different visualisation strategies were employed in two experiments to evaluate the impact of concurrent (KP) and terminal (KR) feedback on the simplification of cognitive processes in learning complex motor skills as well as to enhance their pressure sensitivity and control over applied forces.

In the first experiment, abstract visualisation on location and magnitude of exerted forces by the medical students' palpating hand were provided to semi-visually trained (feedback on training), and visually trained (feedback was provided in both training and test trials) groups to compare their performance with participants in the control group (without any feedback). The captured data from medical students during the actual test trial were assessed in a machine-based and a human-based approach based on the previously defined criterion. Participants in the visually-trained group significantly outperformed the other groups ($H(2) = 6.033$, $p < .05$). The semi-visually trained group performed better than the control group but it was not significant ($p > .05$). The machine-based assessment results were in a positive correlation with the human-based results. Positive responses were received from the medical students who have been trained by the multimodal technology-aided method.

A game-based training approach was used in the second experiment to evaluate the role of serious games in training motor tasks as compared to abstract visualisation techniques. Non-medical participants were trained either with a game-based or an abstract (control) visualisation strategy to perform a simple force application task. The results demonstrate that those players that played the game performed significantly better than a control group in a subsequent no-visual task within a very different environment from the game itself. Moreover, questionnaire responses indicated that the game was enjoyable and engaging.

## 9.2 Limitations

This section presents the major limitations of this research with suggested solutions to overcome these limitations in future work.

- Ergonomics Method: as noted in 4 ethnography (or field study) is one of the most effective methods in ergonomics studies to determine challenges and collect information about conventional practice. However, it is a costly and time consuming method in which the research investigator is physically involved/embedded in the whole training programme (in medical school) for long-term investigations. As part of the future work participation in several formal training sessions is forecast in order to extend the current knowledge about palpation skills.

- Technological Limitations: measuring the human ergonomics demands advancement in sensory technologies and multimodal visualisation displays. Thus, more research is needed in this domain to guide future researchers and developers towards robust and reliable quantification techniques.

- Time and Budget: this work is part of a PhD programme which is tightly constrained in time to conduct several evaluation studies with numerous number of medical students which demands a dedicated research budget. Moreover, participation in this work was completely on voluntarily basis and neither medical experts nor medical students were paid for their contributions. Despite the amazing collaboration level from WMS in this research a systematic recruitment should be considered in a long-term study.

## 9.3 Future Works

Future work will look into enhancing this study by provision of a haptic-enabled natural visualisation technique (eg. a 3D palpation simulator) in future evaluation studies to navigate the medical students' hand movements (the capability of the system to capture location and orientation) as well as providing feedback on force applications (which is proposed in this work). An online version of the ground truth database will be available to all medical experts who teach palpation skills to remotely acquire their palpation performance with ability to compare it with other medical experts as an educational approach for seniors. This will also improve the accuracy and reliability of the gold standard model and minimise the variation between tutors' techniques. In addition, we intend to investigate the impact of our novel training method in other palpation tasks.

Longitudinal studies are planned to evaluate the learning and retention levels in multiple transfer tests (withdrawal of the augmented feedback) with short- and long-term intervals. More broadly, the gold standard database will be used in development of a multipoint haptic display to enhance the medical students' performance in a virtual reality environments with adequately realistic kinaesthetic and cutaneous feedback in conjunction with other modalities. Furthermore, actor patients' abdominal model from various body types and genders in our ground truth study (which is saved as 3D point clouds) are captured by the proposed measurement technique. These information could be provided as a guideline to researchers and developers to form a virtual patient anatomy with realistic deformations of the human soft tissue in haptic rendering domain. Finally, a portable measurement technique with access to the live gold standard model could increase the frequency of rehearsal which is a key feature in palpation training and enhance the medical students' experience in their self-study time with accurate assessment and supervision available in simulation from tutors. Figure 9.1 highlight the future work in Phase II of this research.

Moreover, serious games have shown a potential use in teaching motor skills and further investigation in this field is also planned to evaluate their impact on learning motor skills as compared to abstract and natural visualisation strategies. This work can be then used as a guideline for the development of a serious simulator or serious game with higher level of immersion. Furthermore, palpation is not the only application that requires pressure sensitivity and modifications to the main game to adapt to the range of sensitivities of various applications can aid pressure sensitivity training in other fields (eq. training for musical instruments).

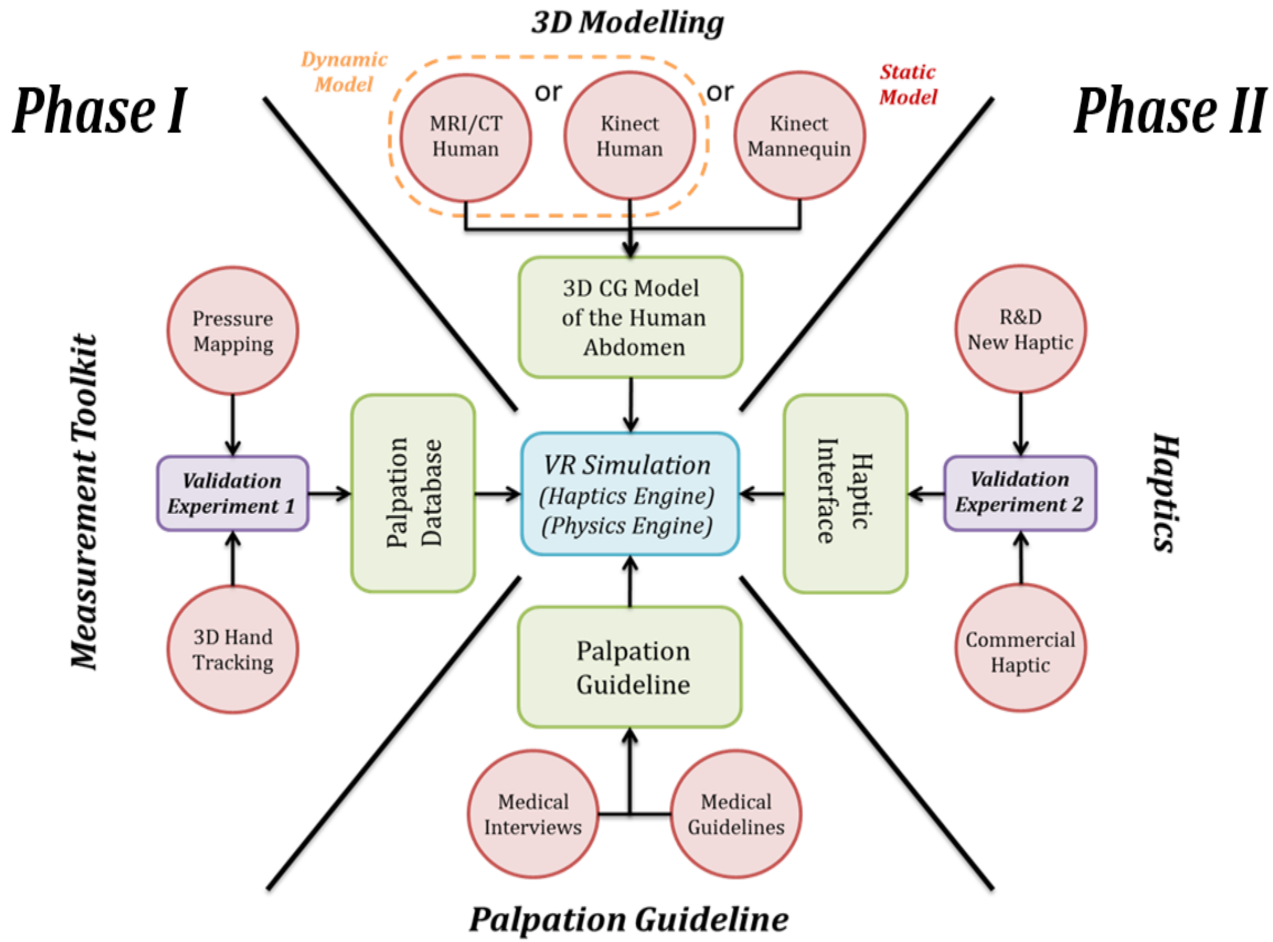



Figure 9.1: Research Roadmap: Phase I is researched in this work; Phase II is potential future works

# Appendices

## A.1

Ethics approval letter

Tuesday 25th June 2013

**Warwick**
**Medical School**

PRIVATE
Mr Ali Asadipour
Warwick Manufacturing Group
Gibbet Hill Road
Coventry
CV4 7AL

Dear Ali,

**Study Title and BSREC Reference:** *Multipoint Haptic-Enabled Abdominal Palpation Training – REGO-2013-239*

Thank you for submitting your revisions to the above-named project to the University of Warwick Biomedical and Scientific Research Ethics Sub-Committee for Chair's Approval.

I am pleased to confirm that I am satisfied that you have met all of the conditions and your application meets the required standard, which means that full approval is granted and your study may commence.

I take this opportunity to wish you success with the study and to remind you any substantial amendments require approval from the committee before they can be made. Please keep a copy of the signed version of this letter with your study documentation.

Yours sincerely,

Graham Hewitt

p.p. Graham Hewitt – BSREC Secretary
David Davies
Chair
Biomedical and Scientific
Research Ethics Sub-Committee

**Biomedical and Scientific**
**Research Ethics Subcommittee**
Enquiries: Amy Ismay
B032 Medical School Building
Warwick Medical School,
Coventry, CV4 7AL.
Tel: 02476-151875
Email: A.C.Ismay@warwick.ac.uk

THE UNIVERSITY OF WARWICK

# A.2

Focus Group - Ground Truth

# Meeting with Medical Experts

***Topic:***
Research into the Potential Use of Haptic-Based Virtual Simulation in Teaching/Assessing Abdominal Palpation Skills

-----------------------------------------------------------------------------------------
Tuesday February 4, 2014
5:00 PM
At International Digital Lab (IDL)

Attendees:
Four medical tutors <Anonymised>
Dr Kurt Debattista, Ali Asadipour (WMG)

## Minutes

### Target Palpation Tasks (Aims)

1. Superficial Palpation (gentle palpation, less pressure)
2. Deep Palpation (more pressure)
3. Palpation of the liver
4. “Agree with previous participants + Palpation of Spleen. esp. edge of middle finger of tutor”

Note: the 4 Abdominal Quadrants

### The Patient/Mannequin Body Size Description

1. Small
2. Medium
3. Large
4. Mannequin: Reference

### To Do List

1. “Pilot Study once sensors are re-designed as discussed.”
2. “Suggest Feasibility Study with humans to validate above.”
3. “Start NHS ethics application”
4. “Then long-term to validate in live clinical setting with variety of ‘normal’ or ‘diseased’ states.”

## Comments

1. How hard is it to learn this task without any physical experience on how to perform it?
   - “Very difficult, simulation will be very helpful”
   - “With any technical or practical task, there is a learning curve.”
   - “Difficult”
2. How accurately medical students can perform this task in their first trial?
   - “Usually poorly - this cause frustration for students and teachers”
   - “Very poor; this is very skilled task that requires much practice.”
   - “It depends on 1) How the have been taught that. 2) The student. Overall not good”
3. How frequent medical students can perform this task in their early years of study?
   - “In practice almost daily – certainly 6-10 times a week in a medical unit.”
   - “They have set tasks & OSCE exams; more frequently as they get more senior”
   - “It depends on ward exposure + practice on friends/family by at least once a week”
4. What is the effect of respiration on palpating this task?
   - “The liver moves up and down.”
   - “Makes it more difficult; timing is critical especially for aims 3, less so far 1 & 2”
   - “Pushes the liver down on deep inspiration. Need to co-ordinate movement of the hand with p’s breathing.”

Other Comments:

- “Great idea! & project!”
- “Much needed + useful tool.”

# A.3

## Competency checklist for examination of gastrointestinal system

| | | | | | |
|---|---|---|---|---|---|
| Student name: | Medical school: Year: | | | | |
| **Examination of the gastrointestinal system**<br>Please examine this patient's gastrointestinal system. | | Self | Peer | Peer/tutor | Tutor |
| Explanation and consent | • Washes hands with alcohol gel or soap and water | ☐ | ☐ | ☐ | ☐ |
| | • Explains procedure to patient and obtains verbal consent | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| Correct position and adequate exposure | • Positions patient flat with one pillow | ☐ | ☐ | ☐ | ☐ |
| | • Adequately exposes the abdomen while maintaining patient dignity | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| General inspection | • Inspects patient from end of bed, commenting on any relevant findings | ☐ | ☐ | ☐ | ☐ |
| | • Inspects patient's surroundings for 'clues' | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| General examination | • Examines hands for palmar erythema, Dupuytren's contracture, and liver flap | ☐ | ☐ | ☐ | ☐ |
| | • Examines nails for clubbing, leuconychia, and koilonychia | ☐ | ☐ | ☐ | ☐ |
| | • Takes the pulse and blood pressure | ☐ | ☐ | ☐ | ☐ |
| | • Assesses axillary lymph nodes | ☐ | ☐ | ☐ | ☐ |
| | • Inspects eyes for jaundice and anaemia | ☐ | ☐ | ☐ | ☐ |
| | • Examines mouth for dentition, angular stomatitis, aphthous ulcers, hydration status, pigmentation, telangiectasia, and candidiasis | ☐ | ☐ | ☐ | ☐ |
| | • Assesses cervical lymph nodes, paying particular attention to the left supraclavicular fossa | ☐ | ☐ | ☐ | ☐ |
| | • Inspects chest for spider naevi and in male subjects for gynaecomastia | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| System examination | • Reinspects abdomen more closely, commenting on any relevant findings | ☐ | ☐ | ☐ | ☐ |
| | • Asks permission to palpate the abdomen, enquires about areas of tenderness, and starts as far away from these as possible | ☐ | ☐ | ☐ | ☐ |
| | • Palpates lightly then deeply in all nine areas | ☐ | ☐ | ☐ | ☐ |
| | • Palpates for liver, spleen, kidneys, bladder, and for abdominal aortic aneurysm | ☐ | ☐ | ☐ | ☐ |
| | • Percusses for liver, spleen, bladder, and shifting dullness | ☐ | ☐ | ☐ | ☐ |
| | • Auscultates for bowel sounds | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| Additional examination | • Assesses the inguinal lymph nodes | ☐ | ☐ | ☐ | ☐ |
| | • Comments on need to examine hernial orifices and external genitalia, and perform rectal examination | ☐ | ☐ | ☐ | ☐ |
| | • Examines for peripheral oedema | ☐ | ☐ | ☐ | ☐ |
| | • | ☐ | ☐ | ☐ | ☐ |
| Professionalism | • Covers patient, thanks patient, washes hands | ☐ | ☐ | ☐ | ☐ |
| Self-assessed as at least borderline: | Signature: Date: | U B S E | U B S E | U B S E | U B S E |
| Peer-assessed as ready for tutor assessment: | Signature: Date: | U B S E | U B S E | U B S E | U B S E |
| Tutor-assessed as satisfactory: | Signature: Date: | U B S E | U B S E | U B S E | U B S E |
| Notes | | | | | |

## A.4

Usability Feedback Form

# Student Evaluation of Teaching Method

WMG Innovative Solutions

| Name: | Gender: | Group: | Time & Date: |
|---|---|---|---|
| Research Title: Multipoint Haptic-Enabled Abdominal Palpation Training | | | |

Please circle the most suitable answer:

- ❖ Please rank yourself if you have tried/done these skills before? Novice / Less Experienced / Average / Experienced / Expert
- ❖ Are you Left Handed? Yes No

Consider the following statements and circle a number:

1 disagree strongly
2 disagree
3 neither agree nor disagree
4 agree
5 agree strongly

| **Innovative tool for Abdominal Palpation training** | | | | | |
|---|---|---|---|---|---|
| 1) This tool has potential as a learning aid for investigation training | 1 | 2 | 3 | 4 | 5 |
| 2) This tool has potential as a learning aid for superficial palpation training | 1 | 2 | 3 | 4 | 5 |
| 3) This tool has potential as a learning aid for deep palpation training | 1 | 2 | 3 | 4 | 5 |
| 4) This tool has potential as a learning aid for locating specific organs (i.e. liver) | 1 | 2 | 3 | 4 | 5 |
| 5) This tool provide a close to real experience | 1 | 2 | 3 | 4 | 5 |
| 6) This tool is comfortable and lightweight to be used as a learning aid | 1 | 2 | 3 | 4 | 5 |
| 7) This tool has potential to contribute to patient safety | 1 | 2 | 3 | 4 | 5 |
| 8) This tool has potential to contribute to patient dignity | 1 | 2 | 3 | 4 | 5 |
| 9) This tool has potential to contribute to patient experience | 1 | 2 | 3 | 4 | 5 |
| 10) This tool is very beneficial to enhance conventional learning methods | 1 | 2 | 3 | 4 | 5 |
| 11) Left/Right handedness may effect on leaning these skills (Left Handed only) | 1 | 2 | 3 | 4 | 5 |
| What did you learn? | | | | | |
| What did you learn extra with this tool? | | | | | |
| Other Comments: | | | | | |

Thank you for taking the time to give us your feedback.

19 June 2013

# Bibliography

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of motor behavior*, 3(2):111–150.

Alahakone, A. U., Senanayake, S., and Arosha, M. (2009). Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display. In *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*, pages 1148–1153. IEEE.

Arnab, S., Dunwell, I., and Debattista, K. (2012). *Serious Games for Healthcare: Applications and Implications: Applications and Implications*. IGI Global.

Batavia, M., Gianutsos, J. G., Vaccaro, A., and Gold, J. T. (2001). A do-it-yourself membrane-activated auditory feedback device for weight bearing and gait training: A case report. *Archives of physical medicine and rehabilitation*, 82(4):541–545.

Bendtsen, L., Jensen, R., Jensen, N., and Olesen, J. (1995). Pressure-controlled palpation: a new technique which increases the reliability of manual palpation. *Cephalalgia*, 15(3):205–210.

Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual review of psychology*, 47(1):431–459.

Bilodeau, E. A. (1966). Acquisition of skill.

Bloom, B. S. and Krathwohl, D. R. (1984). *Taxonomy of educational objectives book 1: Cognitive domain*. Addison Wesley Publishing Company.

Brown, K. E., Bayley, J., and Newby, K. (2012). Serious game for relationships and sex education: Application of an intervention. *Serious Games for Healthcare: Applications and Implications: Applications and Implications*, page 135.

Bunnell, S. (1964). *Surgery of the Hand*. Lippincott.

Carmeli, E., Vatine, J.-J., Peleg, S., Bartur, G., and Elbo, E. (2009). Upper limb rehabilitation using augmented feedback: Impairment focused augmented feedback with handtutor. In *Virtual Rehabilitation International Conference, 2009*, pages 220–220.

Chua, P. T., Crivella, R., Daly, B., Hu, N., Schaaf, R., Ventura, D., Camill, T., Hodgins, J., and Pausch, R. (2003). Training for physical tasks in virtual environments: Tai chi. In *Virtual Reality, 2003. Proceedings. IEEE*, pages 87–94. IEEE.

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences (rev.* Lawrence Erlbaum Associates, Inc.

Coles, T. R., John, N. W., Gould, D., Caldwell, D. G., et al. (2011a). Integrating haptics with augmented reality in a femoral palpation and needle insertion training simulation. *Haptics, IEEE Transactions on*, 4(3):199–209.

Coles, T. R., Meglan, D., and John, N. W. (2011b). The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Transactions on Haptics*, 4(1):51–66.

Collier, K. G. (1985). Teaching methods in higher education: the changing scene, with special reference to small-group work. *Higher Education Research and Development*, 4(1):3–27.

Collins, J. J. and De Luca, C. J. (1993). Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Experimental brain research*, 95(2):308–318.

Committee, I. G. et al. (1964). Report of the committee on university teaching methods (hale committee).

Dinsmore, M., Langrana, N., Burdea, G., and Ladeji, J. (1997). Virtual reality training simulation for palpation of subsurface tumors. In *Virtual Reality Annual International Symposium, 1997., IEEE 1997*, pages 54–60. IEEE.

Dipietro, L., Sabatini, A. M., and Dario, P. (2008). A survey of glove-based systems and their applications. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 38(4):461–482.

Dunwell, I. and Jarvis, S. (2012). A serious game for on-the-ward infection control awareness training: Ward off infection. *Serious Games for Healthcare: Applications and Implications: Applications and Implications*, page 233.

Duvivier, R. J., van Geel, K., van Dalen, J., Scherpbier, A. J., and van der Vleuten, C. P. (2012). Learning physical examination skills outside timetabled training sessions: what happens and why? *Advances in health sciences education*, 17(3):339–355.

Effenberg, A. O. (2005). Movement sonification: Effects on perception and action. *IEEE multimedia*, (2):53–59.

Farrell, J. E. (1975). The classification of physical education skills. *Quest*, 24(1):63–68.

Faul, F., Erdfelder, E., Lang, A.-G., and Buchner, A. (2007). G* power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, 39(2):175–191.

Fitts, P. M. and Posner, M. I. (1967). Human performance.

Florez, J. et al. (2010). Calibration of force sensing resistors (fsr) for static and dynamic applications. In *ANDESCON, 2010 IEEE*, pages 1–6. IEEE.

Fowler, C. A., Turvey, M., and Stelmach, G. E. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. *Information processing in motor control and learning*, pages 1–40.

Frati, V. and Prattichizzo, D. (2011). Using kinect for hand tracking and rendering in wearable haptics. In *World Haptics Conference (WHC), 2011 IEEE*, pages 317–321. IEEE.

Futarmal, S., Kothari, M., Ayesh, E., Baad-Hansen, L., and Svensson, P. (2011). New palpometer with implications for assessment of deep pain sensitivity. *Journal of dental research*, 90(7):918–922.

Gardner, E. P., Martin, J. H., and Jessell, T. M. (2000). The bodily senses. *Principles of neural science*, 4:430–450.

Gentile, A. M. (1972). A working model of skill acquisition with application to teaching. *Quest*, 17(1):3–23.

Goodwin, J. (1995). The importance of clinical skills. *BMJ*, 310(6990):1281–1282.

Gotsis, M. (2009). Games, virtual reality, and the pursuit of happiness. *Computer Graphics and Applications, IEEE*, 29(5):14–19.

Graafland, M., Schraagen, J. M., and Schijven, M. P. (2012). Systematic review of serious games for medical education and surgical skills training. *British Journal of Surgery*, 99(10):1322–1330. Available from: `http://dx.doi.org/10.1002/bjs.8819`.

Hartley, J. and Cameron, A. (1967). Some observations on the efficiency of lecturing. *Educational Review*, 20(1):30–37.

Howell, M. L. (1956). Use of force-time graphs for performance analysis in facilitating motor learning. *Research Quarterly. American Association for Health, Physical Education and Recreation*, 27(1):12–22.

Huegel, J. C. and Malley, M. K. (2010). Progressive haptic and visual guidance for training in a virtual dynamic task. In *Haptics Symposium, 2010 IEEE*, pages 343–350. IEEE.

Jensen, T. R., Radwin, R. G., and Webster, J. G. (1991a). A conductive polymer sensor for measuring external finger forces. *Journal of biomechanics*, 24(9):851–858.

Jensen, T. R., Radwin, R. G., and Webster, J. G. (1991b). A conductive polymer sensor for measuring external finger forces. *Journal of biomechanics*, 24(9):851–858.

Kamel Boulos, M. N. (2011). Healthcybermap. Available from: `http://www.healthcybermap.org/`.

Kamel Boulos, M. N., Hetherington, L., and Wheeler, S. (2007). Second life: an overview of the potential of 3-d virtual worlds in medical and health education. *Health Information & Libraries Journal*, 24(4):233–245. Available from: `http://dx.doi.org/10.1111/j.1471-1842.2007.00733.x`.

Kammermeier, P., Buss, M., and Schmidt, G. (2001). A systems theoretical model for human perception in multimodal presence systems. *Mechatronics, IEEE/ASME Transactions on*, 6(3):234–244.

Kato, P. M., Cole, S. W., Bradlyn, A. S., and Pollock, B. H. (2008). A video game improves behavioral outcomes in adolescents and young adults with cancer: a randomized trial. *Pediatrics*, 122(2):e305–e317.

Kernodle, M. W. and Carlton, L. G. (1992). Information feedback and the learning of multiple-degree-of-freedom activities. *Journal of motor behavior*, 24(2):187–195.

Kitzinger, J. (1995). Qualitative research. introducing focus groups. *BMJ: British medical journal*, 311(7000):299.

Konttinen, N., Mononen, K., Viitasalo, J., Mets, T., et al. (2004). The effects of augmented auditory feedback on psychomotor skill learning in precision shooting. *Journal of Sport and Exercise Psychology*, 26(2):306–316.

Kozma, R. and Freeman, W. J. (2003). Basic principles of the kiv model and its application to the navigation problem. *Journal of Integrative Neuroscience*, 2(01):125–145.

Krathwohl, D. R. (2002). A revision of bloom's taxonomy: An overview. *Theory into practice*, 41(4):212–218.

Lauber, B. and Keller, M. (2014). Improving motor performance: Selected aspects of augmented feedback in exercise and health. *European journal of sport science*, 14(1):36–43.

Lederman, S. J., Martin, A., Tong, C., and Klatzky, R. L. (2003). Relative performance using haptic and/or touch-produced auditory cues in a remote absolute texture identification task. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 11th Symposium on*, pages 151–158. IEEE.

Lin, J., Wu, Y., and Huang, T. S. (2000). Modeling the constraints of human hand motion. In *Human Motion, 2000. Proceedings. Workshop on*, pages 121–126. IEEE.

Lindahl, L. (1945). *Movement Analysis as an Industrial Training Method*. American Psychological Association. Available from: https://books.google.co.uk/books?id=tqSMQwAACAAJ.

Macleod, J., Douglas, G., Nicol, E. F., and Robertson, C. E. (2009). *Macleod's clinical examination*. Elsevier Health Sciences.

Martin, J. L., Murphy, E., Crowe, J. A., and Norris, B. J. (2006). Capturing user requirements in medical device development: the role of ergonomics. *Physiological measurement*, 27(8):R49.

Mavis, B. E. (2000). Does studying for an objective structured clinical examination make a difference? *Medical Education*, 34(10):808–812.

Morphopedics (visited on 2015). Guide to physical therapist practice. Available from: http://morphopedics.wikidot.com/physical-therapy-management-of-colles-fracture.

MRCS (Updated March 2015). Candidate instructions and guidance notes mrcs part b. Available from: http://tools.ietf.org/html/draft-ietf-lisp-alt-07.

Mussa-Ivaldi, F. A., Hogan, N., and Bizzi, E. (1985). Neural, mechanical, and geometric factors subserving arm posture in humans. *The Journal of neuroscience*, 5(10):2732–2743.

National Health System (NHS) Choices (last visit 2015a). Bmi healthy weight calculator. Available from: http://www.nhs.uk/Tools/Pages/Healthyweightcalculator.aspx.

National Health System (NHS) Choices (last visit 2015b). Why body shape matters. Available from: http://www.nhs.uk/Livewell/loseweight/Pages/Appleorpear.aspx.

Newell, K. (1981). Skill learning. in: D.h. holding (ed.). *Human Skills*, pages 203–226.

Newell, K., Carlton, M., and Antoniou, A. (1990). The interaction of criterion and feedback information in learning a drawing task. *Journal of motor behavior*, 22(4):536–552.

Oikonomidis, I., Kyriazis, N., and Argyros, A. A. (2012). Tracking the articulated motion of two strongly interacting hands. In *Computer Vision and Pattern Recognition (CVPR), 2012 IEEE Conference on*, pages 1862–1869. IEEE.

Patel, V. and Morrissey, J. (2011). *Practical and professional clinical skills*. Oxford University Press.

Peacock, B., Westers, T., Walsh, S., and Nicholson, K. (1981). Feedback and maximum voluntary contraction. *Ergonomics*, 24(3):223–228.

Prisacariu, V. A. and Reid, I. (2011). Robust 3d hand tracking for human computer interaction. In *Automatic Face & Gesture Recognition and Workshops (FG 2011), 2011 IEEE International Conference on*, pages 368–375. IEEE.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A.-S., McNamara, J. O., Williams, S. M., et al. (2001). Mechanoreceptors specialized to receive tactile information.

Robles-De-La-Torre, G. (2006). The importance of the sense of touch in virtual and real environments. *Ieee Multimedia*, (3):24–30.

Rogers, Y. (2009). *The changing face of human-computer interaction in the age of ubiquitous computing*. Springer.

Ross, D., Bird, A. M., Doody, S. G., and Zoeller, M. (1985). Effects of modeling and videotape feedback with knowledge of results on motor performance. *Human Movement Science*, 4(2):149–157.

Rothstein, A. L. and Arnold, R. (1976). Bridging the gap: application of research on videotape feedback and bowling. *Motor skills. Theory into practice*, 1:35–64.

Rubin, W. M. (1978). Application of signal detection theory to error detection in ballistic motor skills. *Journal of Experimental Psychology: Human Perception and Performance*, 4(2):311.

Saini, S., Rambli, D., Sulaiman, S., Zakaria, M., and Shukri, S. (2012). A low-cost game framework for a home-based stroke rehabilitation system. In *Computer Information Science (ICCIS), 2012 International Conference on*, volume 1, pages 55–60.

Salamin, P., Tadi, T., Blanke, O., Vexo, F., and Thalmann, D. (2010). Quantifying effects of exposure to the third and first-person perspectives in virtual-reality-based training. *Learning Technologies, IEEE Transactions on*, 3(3):272–276.

Salmoni, A. W., Schmidt, R. A., and Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical reappraisal. *Psychological bulletin*, 95(3):355.

Sauter GmbH (2015). Instruction manual for force gauge fh series. Available from: `http://www.force-gauges.co.uk/pdf/fh-m.pdf`.

Scarle, S., Dunwell, I., Bashford-Rogers, T., Selmanovic, E., Debattista, K., Chalmers, A., Powell, J., and Robertson, W. (2011). Complete motion control of a serious game against obesity in children. In *Games and Virtual Worlds for Serious Applications (VS-GAMES), 2011 Third International Conference on*, pages 178–179.

Scheidt, R. A., Reinkensmeyer, D. J., Conditt, M. A., Rymer, W. Z., and Mussa-Ivaldi, F. A. (2000). Persistence of motor adaptation during constrained, multi-joint, arm movements. *Journal of Neurophysiology*, 84(2):853–862.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological review*, 82(4):225.

Schmidt, R. A. and Lee, T. D. (2005). Motor control and learning: A behavioral emphasis .

Schmidt, R. A. and Wulf, G. (1997). Continuous concurrent feedback degrades skill learning: Implications for training and simulation. *Human factors*, 39(4):509–525.

Schonauer, C., Pintaric, T., Kaufmann, H., Jansen Kosterink, S., and Vollenbroek-Hutten, M. (2011). Chronic pain rehabilitation with a serious game using multimodal input. In *Virtual Rehabilitation (ICVR), 2011 International Conference on*, pages 1–8.

Schutt, R. K. (2011). *Investigating the Social World: The Process and Practice of Research*. SAGE Publications.

ShapeSense (last visit 2015). Body adiposity index calculator. Available from: `http://www.shapesense.com/fitness-exercise/calculators/body-adiposity-index-calculator.aspx`.

Shea, C. H. and Wulf, G. (1999). Enhancing motor learning through external-focus instructions and feedback. *Human Movement Science*, 18(4):553–571.

Sigrist, R., Rauter, G., Riener, R., and Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic bulletin & review*, 20(1):21–53.

Sliney, A. and Murphy, D. (2008). Jdoc: A serious game for medical learning. In *Advances in Computer-Human Interaction, 2008 First International Conference on*, pages 131–136.

Spyridonis, F. and Ghinea, G. (2010). A pilot study to examine the relationship of 3d pain drawings with objective measures in mobility impaired people suffering from low back-pain. In *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE*, pages 3895–3898. IEEE.

Srinivasan, M. A. and Basdogan, C. (1997). Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, 21(4):393–404.

Srinivasan, M. A. and Chen, J.-s. (1993). Human performance in controlling normal forces of contact with rigid objects. *ASME DYN SYST CONTROL DIV PUBL DSC, ASME, NEW YORK, NY,(USA), 1993,*, 49:119–125.

Sturman, D. J. and Zeltzer, D. (1994). A survey of glove-based input. *Computer Graphics and Applications, IEEE*, 14(1):30–39.

Sumo Digital Ltd (last visit 2015). Nike+ Kinect Training. Available from: http://marketplace.xbox.com/en-gb/Product/Nike-Kinect-Training/66acd000-77fe-1000-9115-d8024d53090f.

Susi, T., Johannesson, M., and Backlund, P. (2007). Serious games: An overview.

Tang, M. (2011). Recognizing hand gestures with microsoft's kinect.

Taylor, C. L. and Schwarz, R. J. (1995). The anatomy and mechanics of the human hand.

The Health and Education National Strategic Exchange (HENSE) (last visit 2015). Review of Medical and Dental School Intakes in England. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/213236/medical-and-dental-school-intakes.pdf.

Timmermans, A. A., Seelen, H. A., Willmann, R. D., and Kingma, H. (2009). Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*, 6:1.

Todorov, E., Shadmehr, R., and Bizzi, E. (1997). Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of motor behavior*, 29(2):147–158.

Van Den Heever, D. J., Schreve, K., and Scheffer, C. (2009). Tactile sensing using force sensing resistors and a super-resolution algorithm. *Sensors Journal, IEEE*, 9(1):29–35.

Vredenburg, K., Mao, J.-Y., Smith, P. W., and Carey, T. (2002). A survey of user-centered design practice. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 471–478. ACM.

Wang, R. Y. and Popović, J. (2009a). Real-time hand-tracking with a color glove. *ACM Transactions on Graphics (TOG)*, 28(3):63.

Wang, R. Y. and Popović, J. (2009b). Real-time hand-tracking with a color glove. *ACM Transactions on Graphics (TOG)*, 28(3):63.

Welch, G. F. (1985). A schema theory of how children learn to sing in tune. *Psychology of music*, 13(1):3–18.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical issues in ergonomics science*, 3(2):159–177.

Williams, E. M., Gordon, A. D., and Richmond, B. G. (2012a). Hand pressure distribution during oldowan stone tool production. *Journal of human evolution*, 62(4):520–532.

Williams, E. M., Gordon, A. D., and Richmond, B. G. (2012b). Hand pressure distribution during oldowan stone tool production. *Journal of human evolution*, 62(4):520–532.

Wortley, D. (2013). Immersive technology strategies. *Simulation & Gaming*, 44(2-3):452–465.